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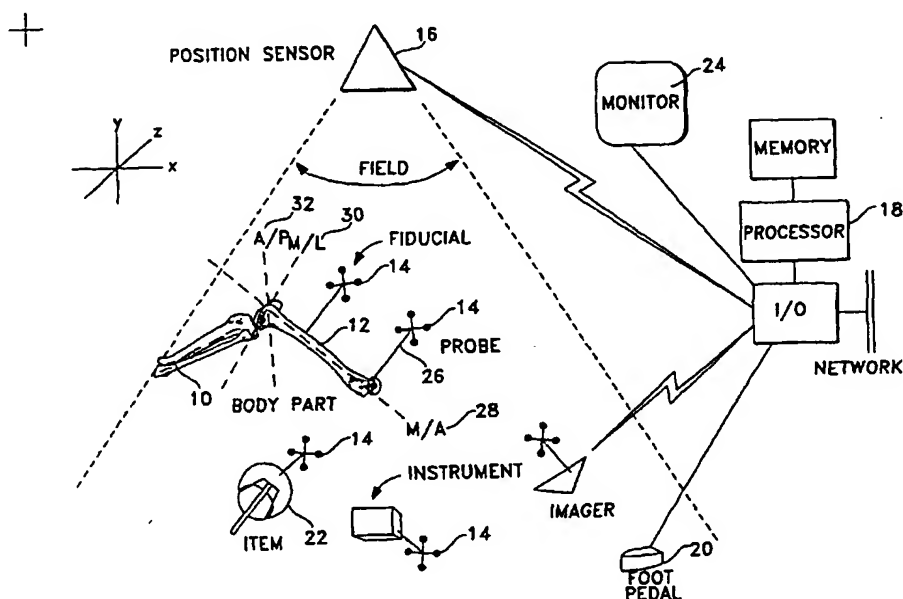
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(54) Title: **SURGICAL NAVIGATION SYSTEMS AND PROCESSES FOR UNICOMPARTMENTAL KNEE**



(57) Abstract: Systems and processes for tracking anatomy, instrumentation, trail implants, implants, and references, and rendering images and data related to them in connection with surgical operations, for example unicompartmental knee arthroplasties ("UKA"). These systems and processes are accomplished by using a computer to intraoperatively obtain images of body parts and to register, navigate, and track surgical instruments.

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**SURGICAL NAVIGATION SYSTEMS AND PROCESSES FOR  
UNICOMPARTMENTAL KNEE ARTHROPLASTY**

**RELATED APPLICATION DATA**

This document claims the benefit of USSN 60/271818, filed February 27, 2001 entitled "Image Guided System for Arthroplasty" and USSN 60/355,899, filed February 11, 2002 entitled "Surgical Navigation Systems and Processes," which documents are incorporated herein by this reference.

**FIELD OF THE INVENTION**

This invention generally relates to unicompartmental knee arthroplasty surgical operations using systems and processes for tracking anatomy, implements, instrumentation, trial implants, implant components and virtual constructs or references, and rendering images and data related to them. Anatomical structures and such items may be attached to or otherwise associated with fiducial functionality, and constructs may be registered in position using fiducial functionality whose position and orientation can be sensed and tracked by systems and according to processes of the present invention in three dimensions in order to perform unicompartmental knee arthroplasty. Such structures, items and constructs can be rendered onscreen properly positioned and oriented relative to each other using associated image files, data files, image input, other sensory input, based on the tracking. Such systems and processes, among other things, allow surgeons to navigate and perform unicompartmental knee arthroplasty using images that reveal interior portions of the body combined with computer generated or transmitted images that show surgical implements, instruments, trials, implants, and/or other devices located and oriented properly relative to the body part. Such systems and processes allow, among other things, more accurate and effective resection of bone, placement and assessment of trial implants and joint performance, and placement and assessment of performance of actual implants and joint performance.

### BACKGROUND

Knee arthroplasty is a surgical procedure in which the articular surfaces of the femur, tibia and patella are cut away and replaced by metal and/or plastic prosthetic components. The goals of knee arthroplasty include  
5 resurfacing the bones in the knee joint and repositioning the joint center on the mechanical axis of the leg. Knee arthroplasty is generally recommended for patients with severe knee pain and disability caused by damage to cartilage from rheumatoid arthritis, osteoarthritis or trauma. It can be highly successful in relieving pain and restoring joint function.

10 More than 95% of knee arthroplasties performed in the United States are tricompartmental knee arthroplasties ("TKA"), which involves the replacement of all the articular surfaces of the knee joint. TKA is performed when arthritis or trauma has affected two or more of the three compartments of the knee: medial compartment (toward the body's central axis), lateral  
15 compartment (away from the body's central axis), and patello-femoral compartment (toward the front of the knee).

The remaining knee arthroplasties are unicompartmental knee arthroplasties ("UKA"). UKA involves the replacement of the articular surfaces of only one knee compartment, usually the medial compartment. UKA is an  
20 attractive surgical treatment for patients with arthritis in only one compartment and with a healthy patella.

UKA has several advantages over TKA. UKA allows the preservation of both cruciate ligaments, while the anterior cruciate ligament is usually removed in TKA. Preservation of the ligaments provides greater stability to  
25 the joint after surgery. UKA also allows for preservation of more bone stock at the joint, which will be beneficial if revision components must be placed. Finally, UKA is less invasive than TKA because UKA requires smaller resections and components.

In spite of these advantages, there continue to be problems in UKA  
30 performance. A leading cause of wear and revision in prosthetics such as knee implants, hip implants and shoulder implants is less than optimum implant alignment. In a UKA, for example, current instrument design for

resection of bone limits the alignment of the femoral and tibial resections to average values for varus/valgus flexion/extension, and external/internal rotation. Additionally, surgeons often use visual landmarks or "rules of thumb" for alignment which can be misleading due to anatomical variability.

5 Intramedullary referencing instruments also violate the femoral and tibial canal. This intrusion increases the risk of fat embolism and unnecessary blood loss in the patient. Surgeons also rely on instrumentation to predict the appropriate implant size for the femur and tibia instead of the ability to intraoperatively template the appropriate size of the implants for optimal

10 performance. Another challenge for surgeons is soft tissue or ligament balancing after the bone resections have been made. Releasing some of the soft tissue points can change the balance of the knee; however, the multiple options can be confusing for many surgeons. Although much of the bone stock remains after UKA, if a revision is necessary, many of the visual

15 landmarks are no longer present, making alignment and restoration of the joint line difficult.

#### SUMMARY

The present invention is applicable not only for knee repair, reconstruction or replacement surgery, but also repair, reconstruction or

20 replacement surgery in connection with any other joint of the body as well as any other surgical or other operation where it is useful to track position and orientation of body parts, non-body components and/or virtual references such as rotational axes, and to display and output data regarding positioning and orientation of them relative to each other for use in navigation and

25 performance of the operation.

Systems and processes according to one embodiment of the present invention use position and/or orientation tracking sensors such as infrared sensors acting stereoscopically or otherwise to track positions of body parts, surgery-related items such as implements, instrumentation, trial prosthetics,

30 prosthetic components, and virtual constructs or references such as rotational axes which have been calculated and stored based on designation of bone landmarks. Processing capability such as any desired form of computer

functionality, whether standalone, networked, or otherwise, takes into account the position and orientation information as to various items in the position sensing field (which may correspond generally or specifically to all or portions or more than all of the surgical field) based on sensed position and orientation of their associated fiducials or based on stored position and/or orientation information. The processing functionality correlates this position and orientation information for each object with stored information regarding the items, such as a computerized fluoroscopic imaged file of a femur or tibia, a wire frame data file for rendering a representation of an instrumentation component, trial prosthesis or actual prosthesis, or a computer generated file relating to a rotational axis or other virtual construct or reference. The processing functionality then displays position and orientation of these objects on a screen or monitor, or otherwise. Thus, systems and processes according to one embodiment of the invention can display and otherwise output useful data relating to predicted or actual position and orientation of body parts, surgically related items, implants, and virtual constructs for use in navigation, assessment, and otherwise performing surgery or other operations.

As one example, images such as fluoroscopy images showing internal aspects of the femur and tibia can be displayed on the monitor in combination with actual or predicted shape, position and orientation of surgical implements, instrumentation components, trial implants, actual prosthetic components, and rotational axes in order to allow the surgeon to properly position and assess performance of various aspects of the knee joint being repaired, reconstructed or replaced. The surgeon may navigate tools, instrumentation, trial prostheses, actual prostheses and other items relative to the femur and tibia in order to perform UKA's more accurately, efficiently, and with better alignment and stability.

Systems and processes according to the present invention can also use the position tracking information and, if desired, data relating to shape and configuration of surgical related items and virtual constructs or references in order to produce numerical data which may be used with or without graphic

imaging to perform tasks such as assessing performance of trial prosthetics statically and throughout a range of motion, appropriately modifying tissue such as ligaments to improve such performance and similarly assessing performance of actual prosthetic components which have been placed in the  
5 patient for alignment and stability.

Systems and processes according to the present invention can also generate data based on position tracking and, if desired, other information to provide cues on screen, aurally or as otherwise desired to assist in the surgery such as suggesting certain bone modification steps or measures  
10 which may be taken to release certain ligaments or portions of them based on performance of components as sensed by systems and processes according to the present invention.

According to a preferred embodiment of systems and processes according to the present invention, at least the following steps are involved:

15 1. Obtain appropriate images such as fluoroscopy images of appropriate body parts such as femur and tibia, the imager being tracked in position via an associated fiducial whose position and orientation is tracked by position/orientation sensors such as stereoscopic infrared (active or passive) sensors according to the present invention.

20 2. Register tools, instrumentation, trial components, prosthetic components, and other items to be used in surgery, each of which corresponds to a fiducial whose position and orientation can be tracked by the position/orientation sensors.

25 3. Locating and registering body structure such as designating points on the femur and tibia using a probe associated with a fiducial in order to provide the processing functionality information relating to the body part such as rotational axes.

30 4. Navigating and positioning instrumentation such as cutting instrumentation in order to modify bone, at least partially using images generated by the processing functionality corresponding to what is being tracked and/or has been tracked, and/or is predicted by the system, and thereby resecting bone effectively, efficiently and accurately.

5. Navigating and positioning trial components such as femoral components and tibial components, some or all of which may be installed using impactors with a fiducial and, if desired, at the appropriate time discontinuing tracking the position and orientation of the trial component using the impactor fiducial and starting to track that position and orientation using the body part fiducial on which the component is installed.

6. Assessing alignment and stability of the trial components and joint, both statically and dynamically as desired, using images of the body parts in combination with images of the trial components while conducting appropriate rotation, anterior-posterior drawer and flexion/extension tests and automatically storing and calculating results to present data or information which allows the surgeon to assess alignment and stability.

7. Releasing tissue such as ligaments if necessary and adjusting trial components as desired for acceptable alignment and stability.

8. Installing implant components whose positions may be tracked at first via fiducials associated with impactors for the components and then tracked via fiducials on the body parts in which the components are installed.

9. Assessing alignment and stability of the implant components and joint by use of some or all tests mentioned above and/or other tests as desired, releasing tissue if desired, adjusting if desired, and otherwise verifying acceptable alignment, stability and performance of the prosthesis, both statically and dynamically.

This process, or processes including it or some of it may be used in any total or partial joint repair, reconstruction or replacement, including knees, hips, shoulders, elbows, ankles and any other desired joint in the body.

Systems and processes according to the present invention represent significant improvement over other previous systems and processes. For instance, systems which use CT and MRI data generally require the placement of reference frames pre-operatively which can lead to infection at the pin site. The resulting 3D images must then be registered, or calibrated, to the patient anatomy intraoperatively. Current registration methods are less accurate than the fluoroscopic system. These imaging modalities are also



more expensive. Some "imageless" systems, or non-imaging systems, require digitizing a large number of points to define the complex anatomical geometries of the knee at each desired site. This can be very time intensive resulting in longer operating room time. Other imageless systems determine  
5 the mechanical axis of the knee by performing an intraoperative kinematic motion to determine the center of rotation at the hip, knee, and ankle. This requires placement of reference frames at the iliac crest of the pelvis and in or on the ankle. This calculation is also time consuming as the system must find multiple points in different planes in order to find the center of rotation. This is  
10 also problematic in patients with pathologic conditions. Ligaments and soft tissues in the arthritic patient are not normal and thus will give a center of rotation that is not desirable for normal knees. Robotic systems require expensive CT or MRI scans and also require preoperative placement of reference frames, usually the day before surgery. These systems are also  
15 much slower, almost doubling operating room time and expense.

None of these systems can effectively track femoral and/or tibial trials during a range of motion and calculate the relative positions of the articular surfaces, among other things. Also, none of them currently make suggestions on ligament balancing, display ligament balancing techniques, or surgical  
20 techniques. Additionally, none of these systems currently track the patella.

An object of certain aspects of the present invention is to use computer processing functionality in combination with imaging and position and/or orientation tracking sensors to present to the surgeon during surgical operations visual and data information useful to navigate, track and/or position  
25 implements, instrumentation, trial components, prosthetic components and other items and virtual constructs relative to the human body in order to improve performance of a repaired, replaced or reconstructed knee joint.

Another object of certain aspects of the present invention is to use computer processing functionality in combination with imaging and position  
30 and/or orientation tracking sensors to present to the surgeon during surgical operations visual and data information useful to assess performance of a knee and certain items positioned therein, including components such as trial

components and prosthetic components, for stability, alignment and other factors, and to adjust tissue and body and non-body structure in order to improve such performance of a repaired, reconstructed or replaced knee joint.

Another object of certain aspects of the present invention is to use  
5 computer processing functionality in combination with imaging and position and/or orientation tracking sensors to present to the surgeon during surgical operations visual and data information useful to show any or all of predicted position and movement of implements, instrumentation, trial components, prosthetic components and other items and virtual constructs relative to the  
10 human body in order to select appropriate components, resect bone accurately, effectively and efficiently, and thereby improve performance of a repaired, replaced or reconstructed knee joint.

Other objects, features and advantages of the present invention are apparent with respect to the remainder of this document.

#### 15 BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic view of a particular embodiment of systems and processes according to the present invention.

Fig. 2 is a view of a knee prepared for surgery, including a femur and a tibia to which fiducials according to one embodiment of the present invention  
20 have been attached.

Fig. 3 is a view of a portion of a leg prepared for surgery according to the present invention with a C-arm for obtaining fluoroscopic images associated with a fiducial according to one embodiment of the present invention.

25 Fig. 4 is a fluoroscopic image of free space rendered on a monitor according to one embodiment of the present invention.

Fig. 5 is a fluoroscopic image of femoral head obtained and rendered according one embodiment of the present invention.

Fig. 6 is a fluoroscopic image of a knee obtained and rendered  
30 according to one embodiment of the present invention.

Fig. 7 is a fluoroscopic image of a tibia distal end obtained and rendered according to one embodiment of the present invention.

Fig. 8 is a fluoroscopic image of a lateral view of a knee obtained and rendered according to one embodiment of the present invention.

Fig. 9 is a fluoroscopic image of a lateral view of a knee obtained and rendered according to one embodiment of the present invention.

5 Fig. 10 is a fluoroscopic image of a lateral view of a tibia distal end obtained and rendered according to one embodiment of the present invention.

Fig. 11 shows a probe according to one embodiment of the present invention being used to register a surgically related component for tracking according to one embodiment of the present invention.

10 Fig. 12 shows a probe according to one embodiment of the present invention being used to register a cutting block for tracking according to one embodiment of the present invention.

Fig. 13 shows a probe according to one embodiment of the present invention being used to register a tibial cutting block for tracking according to one embodiment of the present invention.

Fig. 14 shows a probe according to one embodiment of the present invention being used to register an alignment guide for tracking according to one embodiment of the present invention.

20 Fig. 15 shows a probe according to one embodiment of the present invention being used to designate landmarks on bone structure for tracking according one embodiment of the present invention.

Fig. 16 is another view of a probe according to one embodiment of the present invention being used to designate landmarks on bone structure for tracking according one embodiment of the present invention.

25 Fig. 17 is another view of a probe according to one embodiment of the present invention being used to designate landmarks on bone structure for tracking according one embodiment of the present invention.

Fig. 18 is a screen face produced according to one embodiment of the present invention during designation of landmarks to determine a femoral mechanical axis.

Fig. 19 is a view produced according to one embodiment of the present invention during designation of landmarks to determine a tibial mechanical axis.

5 Fig. 20 is a screen face produced according to one embodiment of the present invention during designation of landmarks to determine an epicondylar axis.

Fig. 21 is a screen face produced according to one embodiment of the present invention during designation of landmarks to determine an anterior-posterior axis.

10 Fig. 22 is a screen face produced according to one embodiment of the present invention during designation of landmarks to determine a posterior condylar axis.

Fig. 23 is a screen face according to one embodiment of the present invention which presents graphic indicia which may be employed to help  
15 determine reference locations within bone structure.

Fig. 24 is a screen face according to one embodiment of the present invention showing mechanical and other axes which have been established according to one embodiment of the present invention.

20 Fig. 25 is another screen face according to one embodiment of the present invention showing mechanical and other axes which have been established according to one embodiment of the present invention.

Fig. 26 is another screen face according to one embodiment of the present invention showing mechanical and other axes which have been established according to one embodiment of the present invention.

25 Fig. 27 shows navigation and placement of an extramedullary rod according to one embodiment of the present invention.

Fig. 28 is another view showing navigation and placement of an extramedullary rod according to one embodiment of the present invention.

30 Fig. 29 is a screen face produced according to one embodiment of the present invention which assists in navigation and/or placement of an extramedullary rod.

Fig. 30 is another view of a screen face produced according to one embodiment of the present invention which assists in navigation and/or placement of an extramedullary rod.

Fig. 31 is a view which shows navigation and placement of an alignment guide according to one embodiment of the present invention.

Fig. 32 is another view which shows navigation and placement of an alignment guide according to one embodiment of the present invention.

Fig. 33 is a view showing placement of an alignment guide according to one embodiment of the present invention.

Fig. 34 is another view showing placement of a cutting block according to one embodiment of the present invention.

Fig. 35 is a view showing navigation and placement of the cutting block of Fig. 45.

Fig. 36 is another view showing navigation and placement of a cutting block according to one embodiment of the present invention.

Fig. 37 is a view showing navigation and placement of a tibial cutting block according to one embodiment of the present invention.

Fig. 38 is a view showing the UKA femoral and tibial implant components.

Fig. 39 is a view showing the UKA femoral and tibial implant components attached at the knee joint.

#### DETAILED DESCRIPTION

Systems and processes according to a preferred embodiment of the present invention use computer capacity, including standalone and/or networked, to store data regarding spatial aspects of surgically related items and virtual constructs or references including body parts, implements, instrumentation, trial components, prosthetic components and rotational axes of body parts. Any or all of these may be physically or virtually connected to or incorporate any desired form of mark, structure, component, or other fiducial or reference device or technique which allows position and/or orientation of the item to which it is attached to be sensed and tracked,

preferably in three dimensions of translation and three degrees of rotation as well as in time if desired.

In a preferred embodiment, orientation of the elements on a particular fiducial varies from one fiducial to the next so that sensors according to the present invention may distinguish between various components to which the fiducials are attached in order to correlate for display and other purposes data files or images of the components. In a preferred embodiment of the present invention, some fiducials use reflective elements and some use active elements, both of which may be tracked by preferably two, sometimes more infrared sensors whose output may be processed in concert to geometrically calculate position and orientation of the item to which the fiducial is attached.

Position/orientation tracking sensors and fiducials need not be confined to the infrared spectrum. Any electromagnetic, electrostatic, light sound, radiofrequency or other desired technique may be used. Alternatively, each item such as a surgical implement, instrumentation component, trial component, implant component or other device may contain its own "active" fiducial such as a microchip with appropriate field sensing or position/orientation sensing functionality and communications link such as spread spectrum RF link, in order to report position and orientation of the item. Such active fiducials, or hybrid active/passive fiducials such as transponders can be implanted in the body parts or in any of the surgically related devices mentioned above, or conveniently located at their surface or otherwise as desired. Fiducials may also take the form of conventional structures such as a screw driven into a bone, or any other three dimensional item attached to another item, position and orientation of such three dimensional item able to be tracked in order to track position and orientation of body parts and surgically related items. Hybrid fiducials may be partly passive, partly active such as inductive components or transponders which respond with a certain signal or data set when queried by sensors according to the present invention.

Systems and processes according to a preferred embodiment of the present invention employ a computer to calculate and store reference axes of body components such as in a UKA, for example, the mechanical axis of the

femur and tibia. From these axes such systems track the position of the instrumentation and osteotomy guides so that bone resections will locate the implant position optimally, usually aligned with the mechanical axis. Furthermore, during trial reduction of the knee, the systems provide feedback on the balancing of the ligaments in a range of motion and under varus/valgus, anterior/posterior and rotary stresses and can suggest or at least provide more accurate information than in the past about which ligaments the surgeon should release in order to obtain correct balancing, alignment and stability. Systems and processes according to the present invention can also suggest modifications to implant size, positioning, and other techniques to achieve optimal kinematics. Systems and processes according to the present invention can also include databases of information regarding tasks such as ligament balancing, in order to provide suggestions to the surgeon based on performance of test results as automatically calculated by such systems and processes.

FIG. 1 is a schematic view showing one embodiment of a system according to the present invention and one version of a setting according to the present invention in which surgery on a knee, in this case a Unicompartmental Knee Arthroplasty, may be performed. Systems and processes according to the present invention can track various body parts such as tibia 10 and femur 12 to which fiducials of the sort described above or any other sort may be implanted, attached, or otherwise associated physically, virtually, or otherwise. In the embodiment shown in FIG. 1, fiducials 14 are structural frames some of which contain reflective elements, some of which contain LED active elements, some of which can contain both, for tracking using stereoscopic infrared sensors suitable, at least operating in concert, for sensing, storing, processing and/or outputting data relating to ("tracking") position and orientation of fiducials 14 and thus components such as 10 and 12 to which they are attached or otherwise associated. Position sensor 16, as mentioned above, may be any sort of sensor functionality for sensing position and orientation of fiducials 14 and therefore items with which they are associated, according to whatever desired electrical, magnetic,

electromagnetic, sound, physical, radio frequency, or other active or passive technique. In the preferred embodiment, position sensor 16 is a pair of infrared sensors disposed on the order of a meter, sometimes more, sometimes less, apart and whose output can be processed in concert to  
5 provide position and orientation information regarding fiducials 14.

In the embodiment shown in FIG. 1, computing functionality 18 can include processing functionality, memory functionality, input/output functionality whether on a standalone or distributed basis, via any desired standard, architecture, interface and/or network topology. In this embodiment,  
10 computing functionality 18 is connected to a monitor on which graphics and data may be presented to the surgeon during surgery. The screen preferably has a tactile interface so that the surgeon may point and click on screen for tactile screen input in addition to or instead of, if desired, keyboard and mouse conventional interfaces. Additionally, a foot pedal 20 or other convenient  
15 interface may be coupled to functionality 18 as can any other wireless or wireline interface to allow the surgeon, nurse or other desired user to control or direct functionality 18 in order to, among other things, capture position/orientation information when certain components are oriented or aligned properly. Items 22 such as trial components, instrumentation  
20 components may be tracked in position and orientation relative to body parts 10 and 12 using fiducials 14.

Computing functionality 18 can process, store and output on monitor 24 and otherwise various forms of data which correspond in whole or part to body parts 10 and 12 and other components for item 22. For example, in the  
25 embodiment shown in FIG. 1, body parts 10 and 12 are shown in cross-section or at least various internal aspects of them such as bone canals and surface structure are shown using fluoroscopic images. These images are obtained using a C-arm attached to a fiducial 14. The body parts, for example, tibia 10 and femur 12, also have fiducials attached. When the  
30 fluoroscopy images are obtained using the C-arm with fiducial 14, a position/orientation sensor 16 "sees" and tracks the position of the fluoroscopy head as well as the positions and orientations of the tibia 10 and femur 12.



The computer stores the fluoroscopic images with this position/orientation information, thus correlating position and orientation of the fluoroscopic image relative to the relevant body part or parts. Thus, when the tibia 10 and corresponding fiducial 14 move, the computer automatically and correspondingly senses the new position of tibia 10 in space and can correspondingly move implements, instruments, references, trials and/or implants on the monitor 24 relative to the image of tibia 10. Similarly, the image of the body part can be moved, both the body part and such items may be moved, or the on screen image otherwise presented to suit the preferences of the surgeon or others and carry out the imaging that is desired. Similarly, when an item 22, such as an extramedullary rod, intramedullary rod, or any other type of rod, that is being tracked moves, its image moves on monitor 24 so that the monitor shows the item 22 in proper position and orientation on monitor 24 relative to the femur 12. The rod 22 can thus appear on the monitor 24 in proper or improper alignment with respect to the mechanical axis and other features of the femur 12, as if the surgeon were able to see into the body in order to navigate and position rod 22 properly

The computer functionality 18 can also store data relating to configuration, size and other properties of items 22 such as implements, instrumentation, trial components, implant components and other items used in surgery. When those are introduced into the field of position/orientation sensor 16, computer functionality 18 can generate and display overlain or in combination with the fluoroscopic images of the body parts 10 and 12, computer generated images of implements, instrumentation components, trial components, implant components and other items 22 for navigation, positioning, assessment and other uses.

Additionally, computer functionality 18 can track any point in the position/orientation sensor 16 field such as by using a designator or a probe 26. The probe also can contain or be attached to a fiducial 14. The surgeon, nurse, or other user touches the tip of probe 26 to a point such as a landmark on bone structure and actuates the foot pedal 20 or otherwise instructs the computer 18 to note the landmark position. The position/orientation sensor 16

"sees" the position and orientation of fiducial 14 "knows" where the tip of probe 26 is relative to that fiducial 14 and thus calculates and stores, and can display on monitor 24 whenever desired and in whatever form or fashion or color, the point or other position designated by probe 26 when the foot pedal 20 is hit or other command is given. Thus, probe 26 can be used to designate landmarks on bone structure in order to allow the computer 18 to store and track, relative to movement of the bone fiducial 14, virtual or logical information such as mechanical axis 28, medial lateral axis 30 and anterior/posterior axis 32 of femur 12, tibia 10 and other body parts in addition to any other virtual or actual construct or reference.

Systems and processes according to an embodiment of the present invention such as the subject of Figs. 2-36, can use the so-called FluoroNAV system and software provided by Medtronic Sofamor Danek Technologies. Such systems or aspects of them are disclosed in USPNs 5,383,454; 5,871,445; 6,146,390; 6,165,81; 6,235,038 and 6,236,875, and related (under 35 U.S.C. Section 119 and/or 120) patents, which are all incorporated herein by this reference. Any other desired systems can be used as mentioned above for imaging, storage of data, tracking of body parts and items and for other purposes.

The FluoroNav system requires the use of reference frame type fiducials 14 which have four and in some cases five elements tracked by infrared sensors for position/orientation of the fiducials and thus of the body part, implement, instrumentation, trial component, implant component, or other device or structure being tracked. Such systems also use at least one probe 26 which the surgeon can use to select, designate, register, or otherwise make known to the system a point or points on the anatomy or other locations by placing the probe as appropriate and signaling or commanding the computer to note the location of, for instance, the tip of the probe. The FluoroNav system also tracks position and orientation of a Cam used to obtain fluoroscopic images of body parts to which fiducials have been attached for capturing and storage of fluoroscopic images keyed to position/orientation information as tracked by the sensors 16. Thus, the

monitor 24 can render fluoroscopic images of bones in combination with computer generated images of virtual constructs and references together with implements, instrumentation components, trial components, implant components and other items used in connection with surgery for navigation, resection of bone, assessment and other purposes.

FIGS. 2 – 39 are various views associated with Unicompartmental Knee Arthroplasty surgery processes according to one particular embodiment and version of the present invention being carried out with the FluoroNav system referred to above. FIG. 2 shows a human knee in the surgical field, as well as the corresponding femur and tibia to which fiducials 14 have been rigidly attached in accordance with this embodiment of the invention. Attachment of fiducials 14 preferably is accomplished using structure that withstands vibration of surgical saws and other phenomenon which occur during surgery without allowing any substantial movement of fiducial 14 relative to body part being tracked by the system.

FIG. 3 shows fluoroscopy images being obtained of the body parts with fiducials 14 attached. The fiducial 14 on the fluoroscopy head in this embodiment is a cylindrically shaped cage which contains LEDs or "active" emitters for tracking by the sensors 16. Fiducials 14 attached to tibia 10 and femur 12 can also be seen. The fiducial 14 attached to the femur 12 uses LEDs instead of reflective spheres and is thus active, fed power by the wire seen extending into the bottom of the image.

FIGS. 4-10 are fluoroscopic images shown on monitor 24 obtained with position and/or orientation information received by, noted and stored within computer 18. FIG. 4 is an open field with no body part image, but which shows the optical indicia which may be used to normalize the image obtained using a spherical fluoroscopy wave front with the substantially flat surface of the monitor 24. FIG. 5 shows an image of the femur 12 head. This image is taken in order to allow the surgeon to designate the center of rotation of the femoral head for purposes of establishing the mechanical axis and other relevant constructs relating to of the femur according to which the prosthetic components will ultimately be positioned. Such center of rotation can be

established by articulating the femur within the acetabulum or a prosthesis to capture a number of samples of position and orientation information and thus in turn to allow the computer to calculate the average center of rotation. The center of rotation can be established by using the probe and designating a number of points on the femoral head and thus allowing the computer to calculate the geometrical center or a center which corresponds to the geometry of points collected. Additionally, graphical representations such as controllably sized circles displayed on the monitor can be fitted by the surgeon to the shape of the femoral head on planar images using tactile input on screen to designate the centers according to that graphic, such as are represented by the computer as intersection of axes of the circles. Other techniques for determining, calculating or establishing points or constructs in space, whether or not corresponding to bone structure, can be used in accordance with the present invention.

FIG. 5 shows a fluoroscopic image of the femoral head while FIG. 6 shows an anterior/posterior view of the knee which can be used to designate landmarks and establish axes or constructs such as the mechanical axis or other rotational axes. FIG. 7 shows the distal end of the tibia and FIG. 8 shows a lateral view of the knee. FIG. 9 shows another lateral view of the knee while FIG. 10 shows a lateral view of the distal end of the tibia.

#### **Registration of Surgically Related Items**

FIGS. 11-14 show designation or registration of items 22 which will be used in surgery. Registration simply means, however it is accomplished, ensuring that the computer knows which body part, item or construct corresponds to which fiducial or fiducials, and how the position and orientation of the body part, item or construct is related to the position and orientation of its corresponding fiducial or a fiducial attached to an impactor or other other component which is in turn attached to an item. Such registration or designation can be done before or after registering bone or body parts as discussed with respect to FIGS. 4 - 10. FIG. 11 shows a technician designating with probe 26 an item 22 such as an instrument component to which fiducial 14 is attached. The sensor 16 "sees" the position and

orientation of the fiducial 14 attached to the item 22 and also the position and orientation of the fiducial 14 attached to the probe 26 whose tip is touching a landmark on the item 22. The technician designates onscreen or otherwise the identification of the item and then activates the foot pedal or otherwise  
5 instructs the computer to correlate the data corresponding to such identification, such as data needed to represent a particular cutting block component for a particular knee implant product, with the particularly shaped fiducial 14 attached to the component 22. The computer has then stored identification, position and orientation information relating to the fiducial for  
10 component 22 correlated with the data such as configuration and shape data for the item 22 so that upon registration, when sensor 16 tracks the item 22 fiducial 14 in the infrared field, monitor 24 can show the cutting block component 22 moving and turning, and properly positioned and oriented relative to the body part which is also being tracked. FIGS. 12-14 show  
15 similar registration for other instrumentation components 22.

#### **Registration of Anatomy and Constructs**

Similarly, the mechanical axis and other axes or constructs of body parts 10 and 12 can also be "registered" for tracking by the system. Again, the system has employed a fluoroscope to obtain images of the femoral head,  
20 knee and ankle of the sort shown in FIGS. 4-10. The system correlates such images with the position and orientation of the C-arm and the patient anatomy in real time as discussed above with the use of fiducials 14 placed on the body parts before image acquisition and which remain in position during the surgical procedure. Using these images and/or the probe, the surgeon can  
25 select and register in the computer 18 the center of the femoral head and ✓ ankle in orthogonal views, usually anterior/posterior and lateral, on a touch screen. The surgeon uses the probe to select any desired anatomical landmarks or references at the operative site of the knee or on the skin or surgical draping over the skin, as on the ankle. These points are registered in  
30 three dimensional space by the system and are tracked relative to the fiducials on the patient anatomy which are preferably placed intraoperatively. FIG. 15 shows the surgeon using probe 26 to designate or register landmarks

on the condylar portion of femur 12 using probe 26 in order to feed to the computer 18 the position of one point needed to determine, store, and display the epicondylar axis. (See FIG. 20 which shows the epicondylar axis and the anterior-posterior plane and for lateral plane.) Although registering points using actual bone structure such as in FIG. 15 is one preferred way to establish the axis, a cloud of points approach by which the probe 26 is used to designate multiple points on the surface of the bone structure can be employed, as can moving the body part and tracking movement to establish a center of rotation as discussed above. Once the center of rotation for the femoral head and the condylar component have been registered, the computer is able to calculate, store, and render, and otherwise use data for, the mechanical axis of the femur 12. FIG. 17 once again shows the probe 26 being used to designate points on the condylar component of the femur 12.

FIG. 18 shows the onscreen images being obtained when the surgeon registers certain points on the bone surface using the probe 26 in order to establish the femoral mechanical axis. The tibial mechanical axis is then established by designating points to determine the centers of the proximal and distal ends of the tibia so that the mechanical axis can be calculated, stored, and subsequently used by the computer 18. FIG. 20 shows designated points for determining the epicondylar axis, both in the anterior/posterior and lateral planes while FIG. 21 shows such determination of the anterior-posterior axis as rendered onscreen. The posterior condylar axis is also determined by designating points or as otherwise desired, as rendered on the computer generated geometric images overlain or displayed in combination with the fluoroscopic images, all of which are keyed to fiducials 14 being tracked by sensors 16.

FIG. 23 shows an adjustable circle graphic which can be generated and presented in combination with orthogonal fluoroscopic images of the femoral head, and tracked by the computer 18 when the surgeon moves it on screen in order to establish the centers of the femoral head in both the anterior-posterior and lateral planes.

FIG. 24 is an onscreen image showing the anterior-posterior axis, epicondylar axis and posterior condylar axis from points which have been designated as described above. These constructs are generated by the computer 18 and presented on monitor 24 in combination with the fluoroscopic images of the femur 12, correctly positioned and oriented relative thereto as tracked by the system. In the fluoroscopic/computer generated image combination shown at left bottom of FIG. 24, a "sawbones" knee as shown in certain drawings above which contains radio opaque materials is represented fluoroscopically and tracked using sensor 16 while the computer generates and displays the mechanical axis of the femur 12 which runs generally horizontally. The epicondylar axis runs generally vertically, and the anterior/posterior axis runs generally diagonally. The image at bottom right shows similar information in a lateral view. Here, the anterior-posterior axis runs generally horizontally while the epicondylar axis runs generally diagonally, and the mechanical axis generally vertically.

FIG. 24, as is the case with a number of screen presentations generated and presented by the system of FIGS. 4–39, also shows at center a list of landmarks to be registered in order to generate relevant axes and constructs useful in navigation, positioning and assessment during surgery. Textural cues may also be presented which suggest to the surgeon next steps in the process of registering landmarks and establishing relevant axes. Such instructions may be generated as the computer 18 tracks, from one step to the next, registration of items 22 and bone locations as well as other measures being taken by the surgeon during the surgical operation.

FIG. 25 shows mechanical, lateral, anterior-posterior axes for the tibia according to points are registered by the surgeon.

FIG. 26 is another onscreen image showing the axes for the femur 12.

Any desired axes or other constructs can be created, tracked and displayed, in order to model and generate images and data showing any desired static or kinematic function of the knee for any purposes related to a UKA.

### Modifying Bone

After the mechanical axis and other rotation axes and constructs relating to the femur and tibia are established, instrumentation can be properly oriented to resect or modify bone in order to fit trial components and implant components properly according to the embodiment of the invention shown in FIGS. 4 - 39. Instrumentation such as, for instance, cutting blocks, to which fiducials 14 are mounted, can be employed. The system can then track instrumentation as the surgeon manipulates it for optimum positioning. In other words, the surgeon can "navigate" the instrumentation for optimum positioning using the system and the monitor. In this manner, instrumentation may be positioned according to the system of this embodiment in order to align the osteotomies to the mechanical and rotational axes or reference axes on an extramedullary rod that does not violate the canal, on an intramedullary rod, or on any other type of rod. The touchscreen 24 can then also display the instrument such as the cutting block and/or the implant relative to the instrument and the rod during this process, in order, among other things, properly to select size of implant and perhaps implant type. As the instrument moves, the varus/valgus, flexion/extension and internal/external rotation of the relative component position can be calculated and shown with respect to the referenced axes; in the preferred embodiment, this can be done at a rate of six cycles per second or faster. The instrument position is then fixed in the computer and physically and the bone resections are made.

FIG. 27 shows orientation of an extramedullary rod to which a fiducial 14 is attached via impactor 22. The surgeon views the screen 24 which has an image as shown in FIG. 29 of the rod overlain on or in combination with the femur 12 fluoroscopic image as the two are actually positioned and oriented relative to one another in space. The surgeon then navigates the rod into place preferably along the mechanical axis of the femur and drives it home with appropriate mallet or other device. The present invention thus avoids the need to bore a hole in the metaphysis of the femur and place a reamer or



other rod into the medullary canal which can cause fat embolism, hemorrhaging, infection and other untoward and undesired effects.

FIG. 28 also shows the extramedullary rod being located. FIG. 29 shows fluoroscopic images, both anterior-posterior and lateral, with axes, and  
5 with a computer generated and tracked image of the rod superposed or in combination with the fluoroscopic images of the femur and tibia. FIG. 30 shows the rod superimposed on the femoral fluoroscopic image similar to what is shown in FIG. 29.

FIG. 29 also shows other information relevant to the surgeon such as  
10 the name of the component being overlain on the femur image, suggestions or instructions at the lower left, and angle of the rod in varus/valgus and extension relative to the axes. Any or all of this information can be used to navigate and position the rod relative to the femur. At a point in time during or after placement of the rod, its tracking may be "handed off" from the impactor  
15 fiducial 14 to the femur fiducial 14 as discussed below.

Once the extramedullary rod, intramedullary rod, or any other type of rod has been placed, instrumentation can be positioned as tracked in position and orientation by sensor 16 and displayed on screen face 24. Thus, a cutting block of the sort used to establish the condylar anterior cut, with its  
20 fiducial 14 attached, is introduced into the field and positioned on the rod. Because the cutting block corresponds to a particular implant product and can be adjusted and designated on screen to correspond to a particular implant size of that product, the computer 18 can generate and display a graphic of the cutting block and the femoral component overlain on the fluoroscopic  
25 image. The surgeon can thus navigate and position the cutting block on screen using not only images of the cutting block on the bone, but also images of the corresponding femoral component which will be ultimately installed. The surgeon can thus adjust the positioning of the physical cutting  
30 block component, and secure it to the rod in order to resect the anterior of the condylar portion of the femur in order to optimally fit and position the ultimate femoral component being shown on the screen. Other cutting blocks and

other resections may be positioned and made similarly on the condylar component.

In a similar fashion, instrumentation may be navigated and positioned on the proximal portion of the tibia 10 and as tracked by sensor 16 and on screen by images of the cutting block and the implant component.

FIGS. 33-37 show instrumentation being positioned relative to femur 12 as tracked by the system for resection of the condylar component in order to receive a particular size of implant component. Various cutting blocks and their attached fiducials can be seen in these views.

#### 10 **Navigation, Placement and Assessment of Trials and Implants**

Once resection and modification of bone has been accomplished, implant trials can then be installed and tracked by the system in a manner similar to navigating and positioning the instrumentation, as displayed on the screen 24. Thus, a femoral component trial, a tibial plateau trial, and a bearing plate trial may be placed as navigated on screen using computer generated overlays corresponding to the trials.

During the trial installation process, and also during the implant component installation process, instrument positioning process or at any other desired point in surgical or other operations according to the present invention, the system can transition or segue from tracking a component according to a first fiducial to tracking the component according to a second fiducial. Thus, the trial femoral component is mounted on an impactor to which is attached a fiducial 14. The trial component is installed and positioned using the impactor. The computer 18 "knows" the position and orientation of the trial relative to the fiducial on the impactor (such as by prior registration of the component attached to the impactor) so that it can generate and display the image of the femoral component trial on screen 24 overlaid on the fluoroscopic image of the condylar component. At any desired point in time, before, during or after the trial component is properly placed on the condylar component of the femur to align with mechanical axis and according to proper orientation relative to other axes, the system can be instructed by foot pedal or otherwise to begin tracking the position of the trial component

using the fiducial attached to the femur rather than the one attached to the impactor. According to the preferred embodiment, the sensor 16 "sees" at his point in time both the fiducials on the impactor and the femur 12 so that it already "knows" the position and orientation of the trial component relative to the fiducial on the impactor and is thus able to calculate and store for later use the position and orientation of the trial component relative to the femur 12 fiducial. Once this "handoff" happens, the impactor can be removed and the trial component tracked with the femur fiducial 14 as part of or moving in concert with the femur 12. Similar handoff procedures may be used in any other instance as desired in accordance with the present invention.

Alternatively, the tibial trial can be placed on the proximal tibia and then registered using the probe 26. Probe 26 is used to designate preferably at least three features on the tibial trial of known coordinates, such as bone spike holes. As the probe is placed onto each feature, the system is prompted to save that coordinate position so that the system can match the tibial trial's feature's coordinates to the saved coordinates. The system then tracks the tibial trial relative to the tibial anatomical reference frame.

Once the trial components are installed, the surgeon can assess alignment and stability of the components and the joint. During such assessment, in trial reduction, the computer can display on monitor 24 the relative motion between the trial components to allow the surgeon to make soft tissue releases and changes in order to improve the kinematics of the knee. The system can also apply rules and/or intelligence to make suggestions based on the information such as what soft tissue releases to make if the surgeon desires. The system can also display how the soft tissue releases are to be made.

During this assessment, the surgeon may conduct certain assessment processes such as external/internal rotation or rotary laxity testing, varus/valgus tests, and anterior-posterior drawer at 0 and 90 degrees and mid range. Thus, in the AP drawer test, the surgeon can position the tibia at the first location and press the foot pedal. He then positions the tibia at the second location and once again presses the foot pedal so that the computer

has registered and stored two locations in order to calculate and display the drawer and whether it is acceptable for the patient and the product involved. If not, the computer can apply rules in order to generate and display suggestions for releasing ligaments or other tissue, or using other component sizes or types. Once the proper tissue releases have been made, if necessary, and alignment and stability are acceptable as noted quantitatively on screen about all axes, the trial components may be removed and actual components navigated, installed, and assessed in performance in a manner similar to that in which the trial components were navigated, installed, and assessed.

At the end of the case, all alignment information can be saved for the patient file. This is of great assistance to the surgeon due to the fact that the outcome of implant positioning can be seen before any resectioning has been done on the bone. The system is also capable of tracking the patella and resulting placement of cutting guides and the patellar trial position. The system then tracks alignment of the patella with the patellar femoral groove and will give feedback on issues, such as, patellar tilt.

The tracking and image information provided by systems and processes according to the present invention facilitate telemedical techniques, because they provide useful images for distribution to distant geographic locations where expert surgical or medical specialists may collaborate during surgery. Thus, systems and processes according to the present invention can be used in connection with computing functionality 18 which is networked or otherwise in communication with computing functionality in other locations, whether by PSTN, information exchange infrastructures such as packet switched networks including the Internet, or as otherwise desire. Such remote imaging may occur on computers, wireless devices, videoconferencing devices or in any other mode or on any other platform which is now or may in the future be capable of rendering images or parts of them produced in accordance with the present invention. Parallel communication links such as switched or unswitched telephone call connections may also accompany or form part of such telemedical techniques. Distant databases such as online

catalogs of implant suppliers or prosthetics buyers or distributors may form part of or be networked with functionality 18 to give the surgeon in real time access to additional options for implants which could be procured and used during the surgical operation.

5

What is claimed is:

1. A process for performing unicompartmental knee arthroplasty surgical operations on portions of a knee joint, comprising:
  - 5 (a) obtaining at least one image of a body part forming a portion of said joint with an imager, wherein the body part and the imager are each attached to a fiducial capable of being tracked by at least one position sensor;
  - (b) registering a surgical instrument attached to a fiducial capable of being tracked by at least one position sensor;
  - 10 (c) using a computer which receives signals from the at least one sensor, tracking position and orientation of the surgical instrument relative to the body part;
  - (d) generating and displaying on a monitor associated with the computer a visual image of the instrument properly positioned and oriented relative to the  
15 body part;
  - (e) navigating the surgical instrument relative to the body part and attaching the surgical instrument to the body part according to the image;
  - (f) modifying the body part using the surgical instrument attached to the body part; and
  - 20 (g) assessing performance of the joint using images displayed on said monitor.
2. A process according to claim 1 further comprising:
  - (a) registering a trial component attached to a fiducial capable of being  
25 tracked by at least one position sensor;
  - (b) removing the instrument from the body part;
  - (c) tracking position and orientation of the trial component relative to the body part;
  - (d) generating and displaying on the monitor a visual image of the trial  
30 component properly positioned and oriented relative to the body part;
  - (e) navigating and installing the trial component on the body part according to the image; and

(f) assessing performance of the knee joint using images displayed on the monitor.

3. A process for performing unicompartmental knee arthroplasty surgical operations on portions of a knee joint, comprising:

(a) obtaining at least one image of a body part forming a portion of said joint with an imager, wherein the body part and the imager are each attached to a fiducial capable of being tracked by at least one position sensor;

(b) registering a unicompartmental knee arthroplasty prosthetic implant component attached to a fiducial capable of being tracked by at least one position sensor;

(c) using a computer which receives signals from the at least one sensor, tracking position and orientation of the implant component relative to the body part;

(d) generating and displaying on a monitor associated with the computer a visual image of the implant component properly positioned and oriented relative to the body part; and

(e) navigating the implant component relative to the body part and attaching the implant to the body part according to the image.

20

4. A process according to claim 2 further comprising:

(a) registering an implant component attached to a tool which is in turn attached to a fiducial;

(b) tracking position and orientation of the implant component relative to the body part;

(c) generating and displaying on the monitor a visual image of the implant component positioned and oriented relative to the body part; and

(d) navigating the implant component relative to the body part and installing the implant component in the body part according to the image.

30

5. A process according to claim 2, 3 or 4, further comprising:

(a) discontinuing tracking of the component using the fiducial attached to the component; and

(b) initiating tracking of the component using the fiducial attached to the body part on which the component is installed.

6. A process according to claim 2, 3 or 4 further comprising:

5 (a) performing soft tissue balancing tests while the computer continues to track the fiducials;

(b) using data generated by the computer to assess alignment and stability of the component and the knee joint; and

(c) releasing soft tissue to adjust alignment and stability of the knee joint.

10

7. A system for performing unicompartmental knee arthroplasty surgical operations on portions of a knee joint comprising:

(a) an imager for obtaining an image of at least portions of the knee joint, wherein the imager and at least one bone forming part of the knee joint are each  
15 attached to a fiducial capable of being tracked by a position sensor;

(b) at least one position sensor adapted to track position of said fiducials;

(c) a computer adapted to store at least one image of at least portions of the knee joint and to receive information from said at least one sensor in order to track position and orientation of said fiducials and thus the knee joint;

20 (d) a unicompartmental knee arthroplasty surgical instrument component adapted to be attached to bone forming part of the knee joint using a tool, said tool attached to a fiducial, whereby the position of the surgical instrument component is capable of being tracked by said sensor and the position and orientation of the surgical instrument component is capable of being tracked by  
25 said computer;

(e) a monitor adapted to receive information from the computer in order to display at least one image of the surgical instrument component, positioned and oriented relative to the knee joint for navigation and positioning of the surgical instrument component relative to the knee joint.

30

8. A system for performing unicompartmental knee arthroplasty surgical operations on portions of a knee joint comprising:



(a) an imager for obtaining an image of at least portions of the knee joint, wherein the imager and the femur are each attached to a fiducial capable of being tracked by a position sensor;

(b) at least one position sensor adapted to track position of said fiducials;

5 (c) a computer adapted to store at least one image of at least portions of the knee joint and to receive information from said at least one sensor in order to track position and orientation of said fiducials and thus the knee joint;

(d) a unicompartmental knee arthroplasty implant trial component adapted to be attached to bone forming part of the knee joint using a tool, said tool  
10 attached to a fiducial, whereby the position of the trial component is capable of being tracked by said sensor and the position and orientation of the trial component is capable of being tracked by said computer;

(e) a monitor adapted to receive information from the computer in order to display at least one image of the trial component, positioned and oriented relative  
15 to the knee joint for navigation and positioning of the trial component relative to the knee joint.

9. A system for performing unicompartmental knee arthroplasty surgical operations on portions of a knee joint comprising:

20 (a) an imager for obtaining an image of at least portions of the knee joint, wherein the imager and the femur are each attached to a fiducial capable of being tracked by a position sensor;

(b) at least one position sensor adapted to track position of said fiducials;

(c) a computer adapted to store at least one image of at least portions of  
25 the knee joint and to receive information from said at least one sensor in order to track position and orientation of said fiducials and thus the knee joint;

(d) a unicompartmental knee arthroplasty implant component adapted to be attached to bone forming part of the knee joint using a tool, said tool attached to a fiducial, whereby the position of the implant component is capable of being  
30 tracked by said sensor and the position and orientation of the implant component is capable of being tracked by said computer;

(e) a monitor adapted to receive information from the computer in order to display at least one image of the implant component, positioned and oriented

relative to the knee joint for navigation and positioning of the implant component relative to the knee joint.

10. A system according to claim 7 in which the instrument component is a  
5 rod.

11. A system according to claim 7 in which the instrument component is a cutting block.

10 12. A system according to claim 10 in which the rod is an intramedullary rod.

13. A system according to claim 10 in which the rod is an extramedullary  
15 rod.

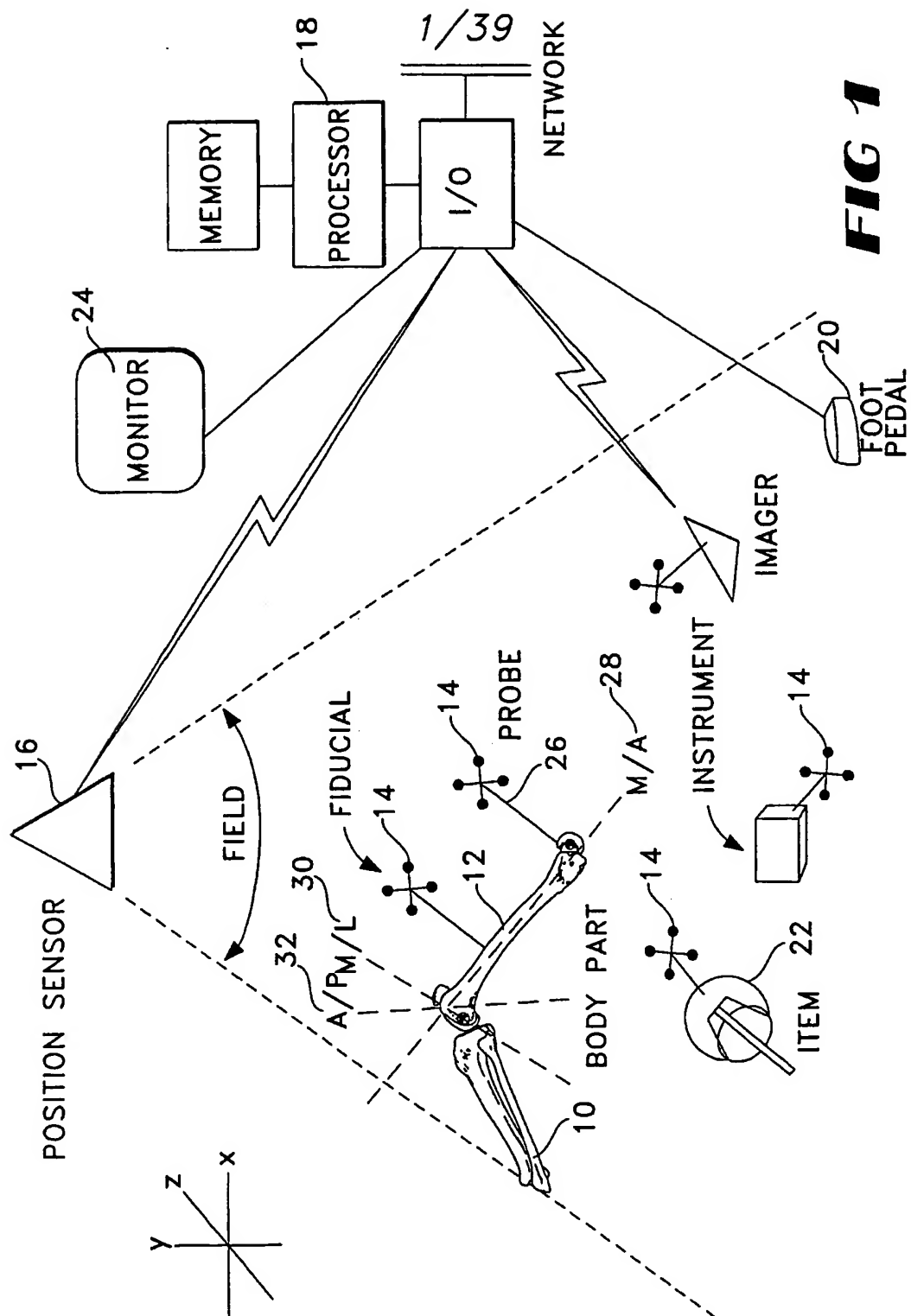
14. A system according to claim 7, 8 or 9 in which the component corresponds to a femur.

15 15. A system according to claim 7, 8 or 9 in which the component  
20 corresponds to a tibia.

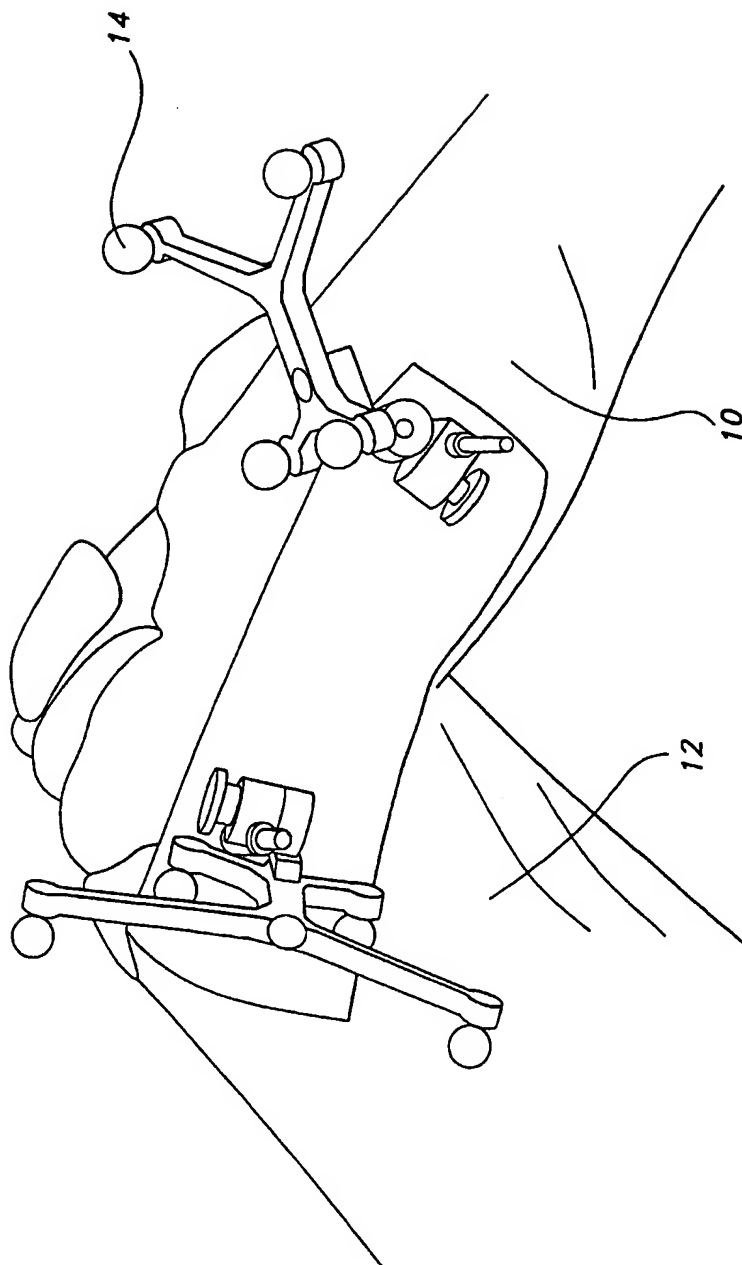
16. A system according to claim 7, 8 or 9 in which the imager comprises one of a C-arm fluoroscope, a CT scanner, and an MRI machine.

25 17. A system according to claim 7, 8 or 9 in which the fiducials comprise one of active fiducials, passive fiducials and hybrid active/passive fiducials.

18. A system according to claim 7, 8 or 9 in which the position sensors  
comprise one of infrared sensors, electromagnetic sensors, electrostatic sensors,  
30 light sensors, sound sensors, and radiofrequency sensors.

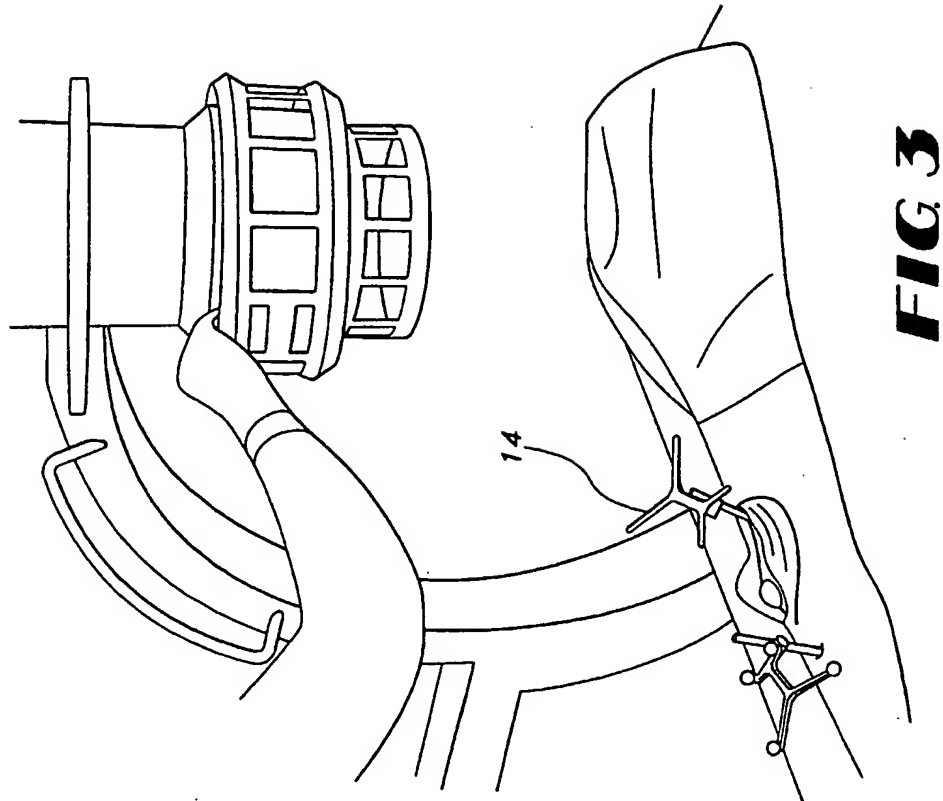


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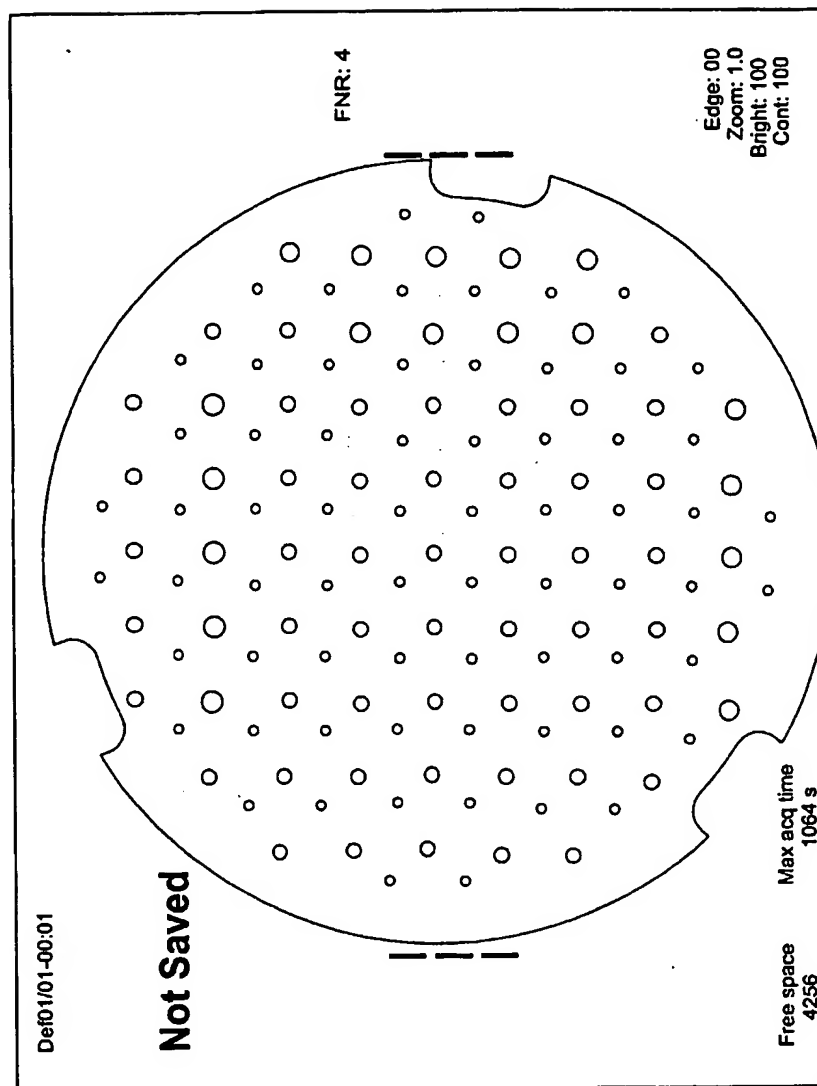


**FIG. 2**

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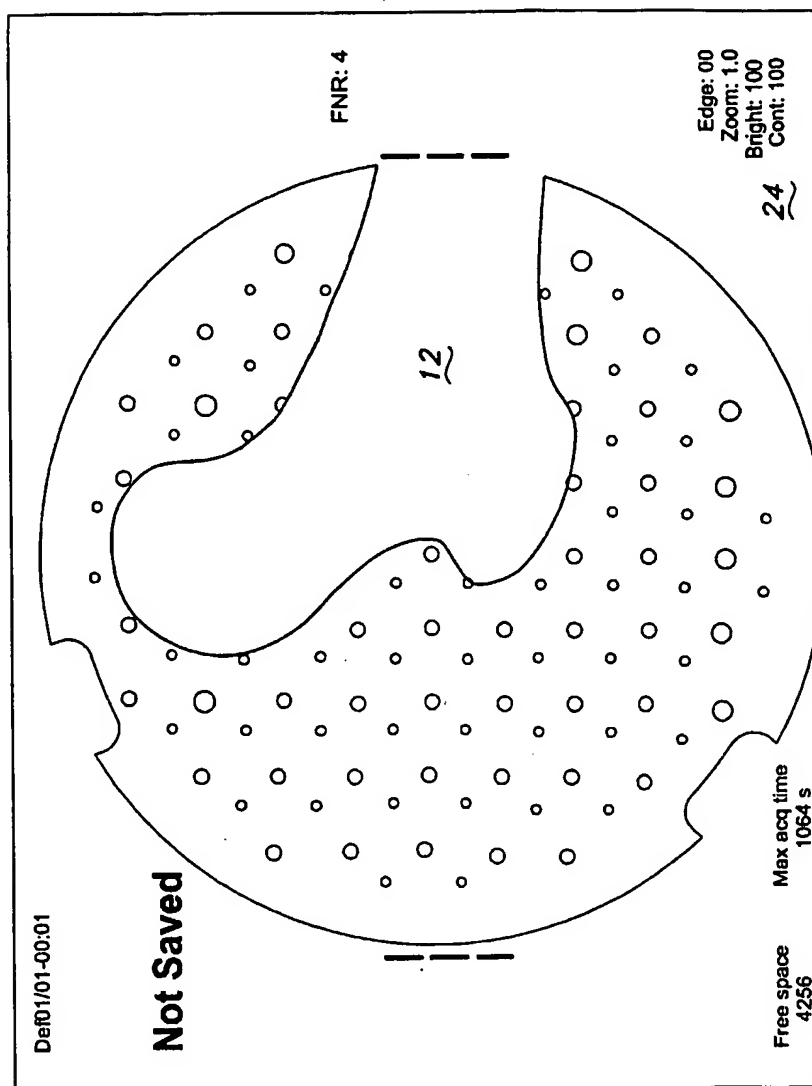


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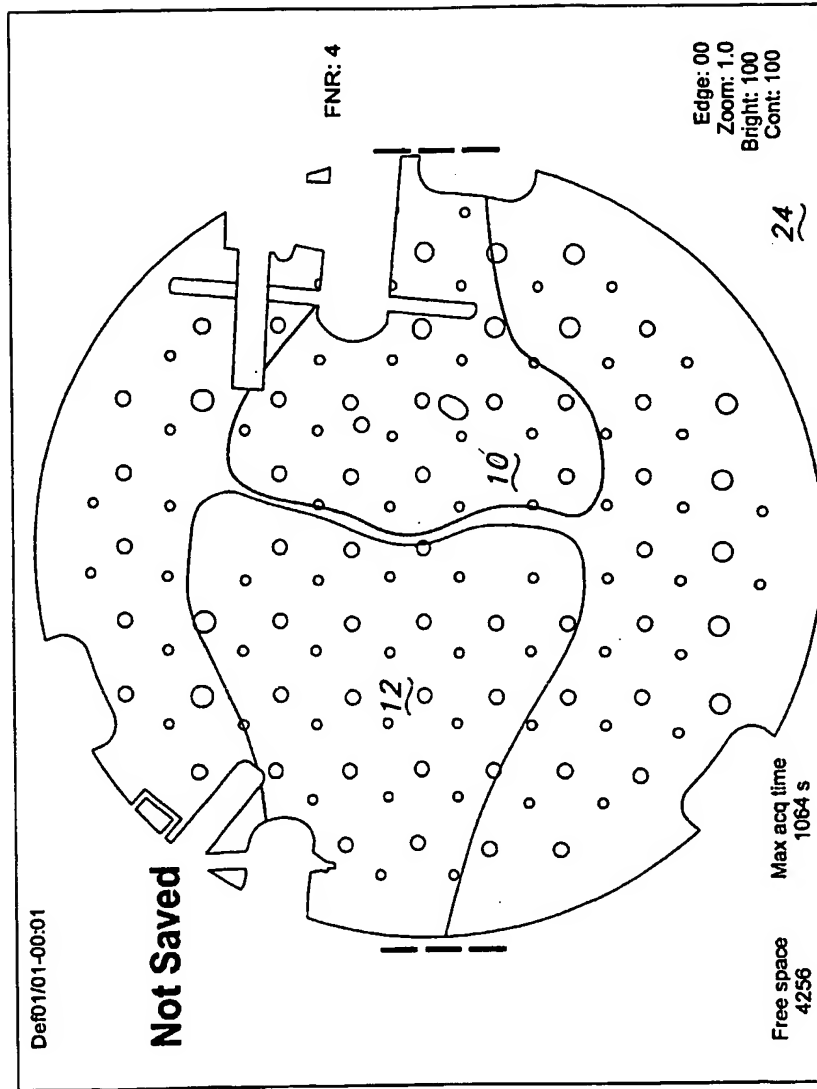
**FIG 4**

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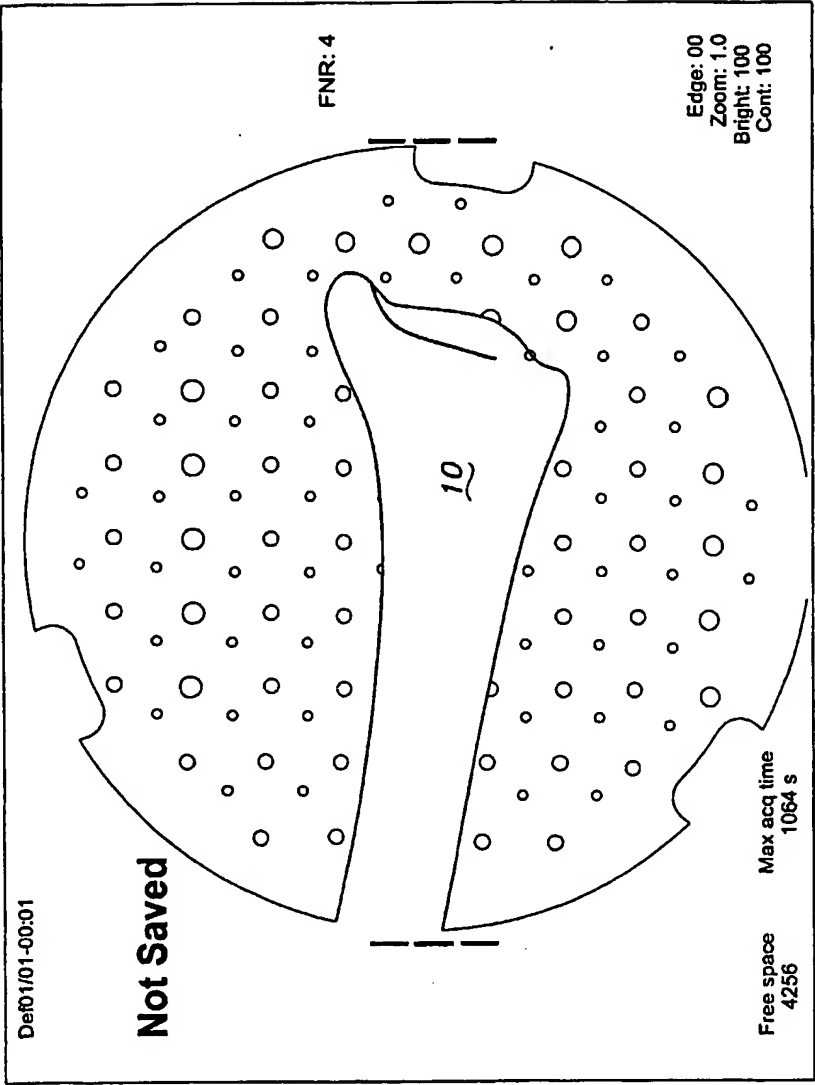
**FIG 5**

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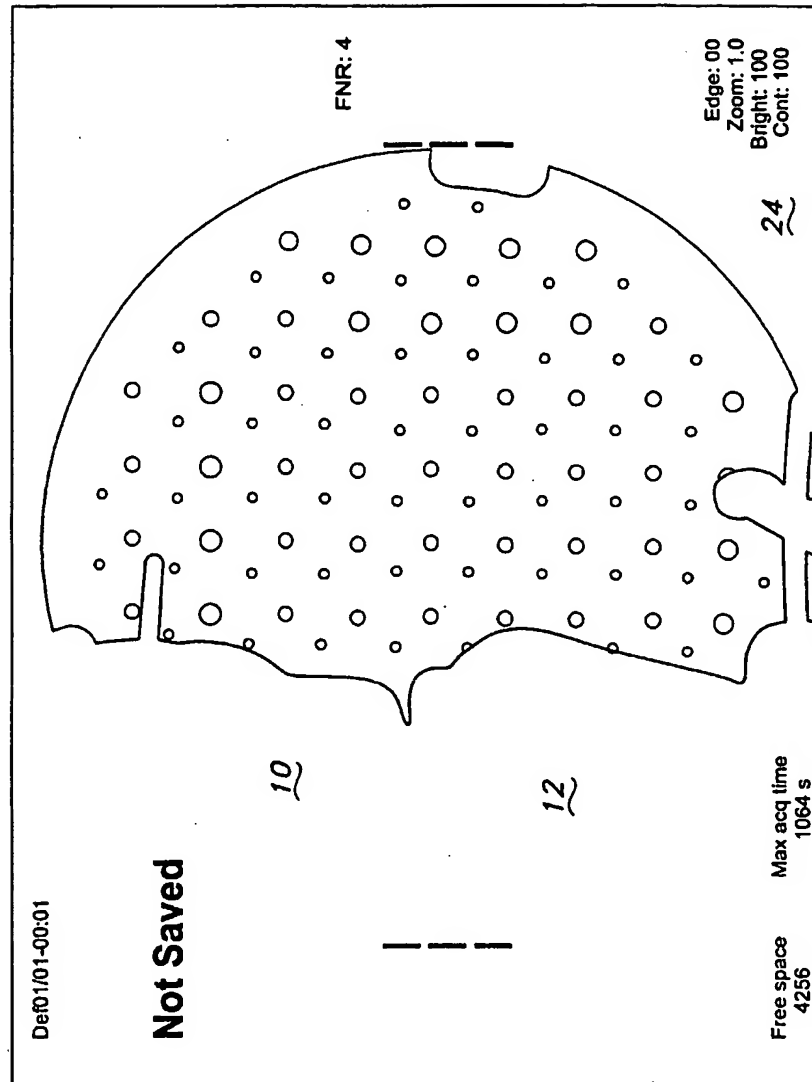
**FIG 6**





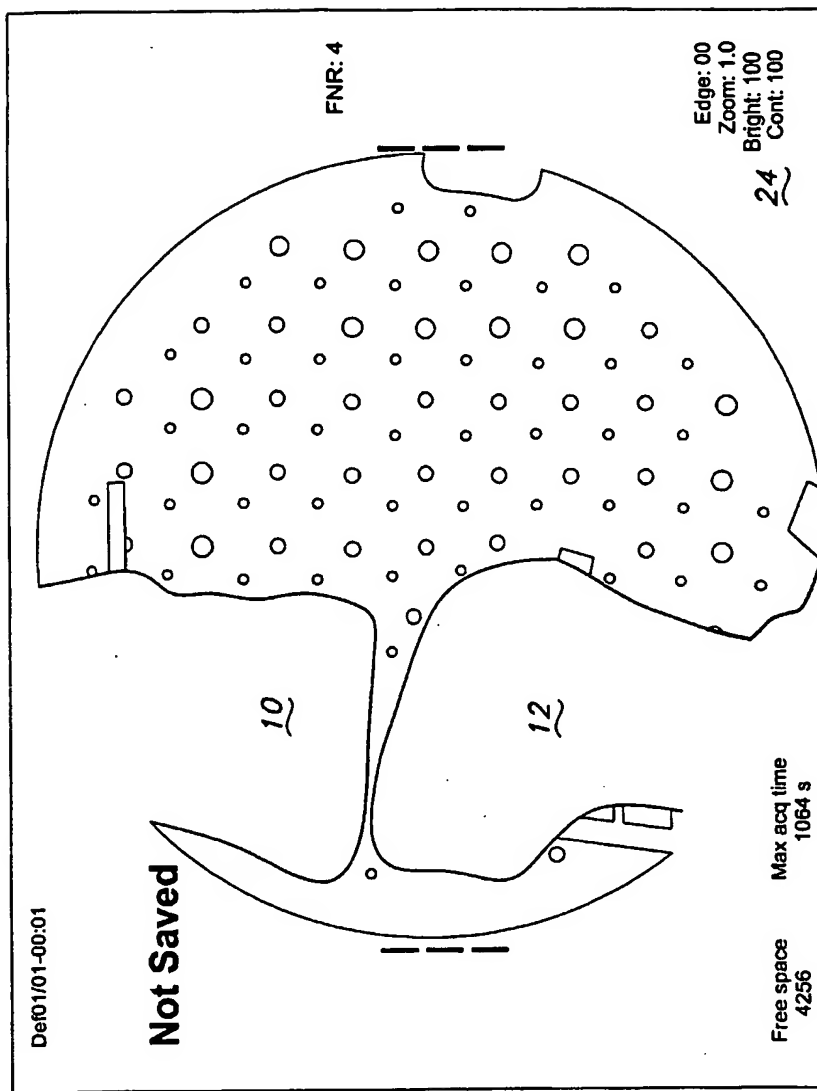
**FIG 7**

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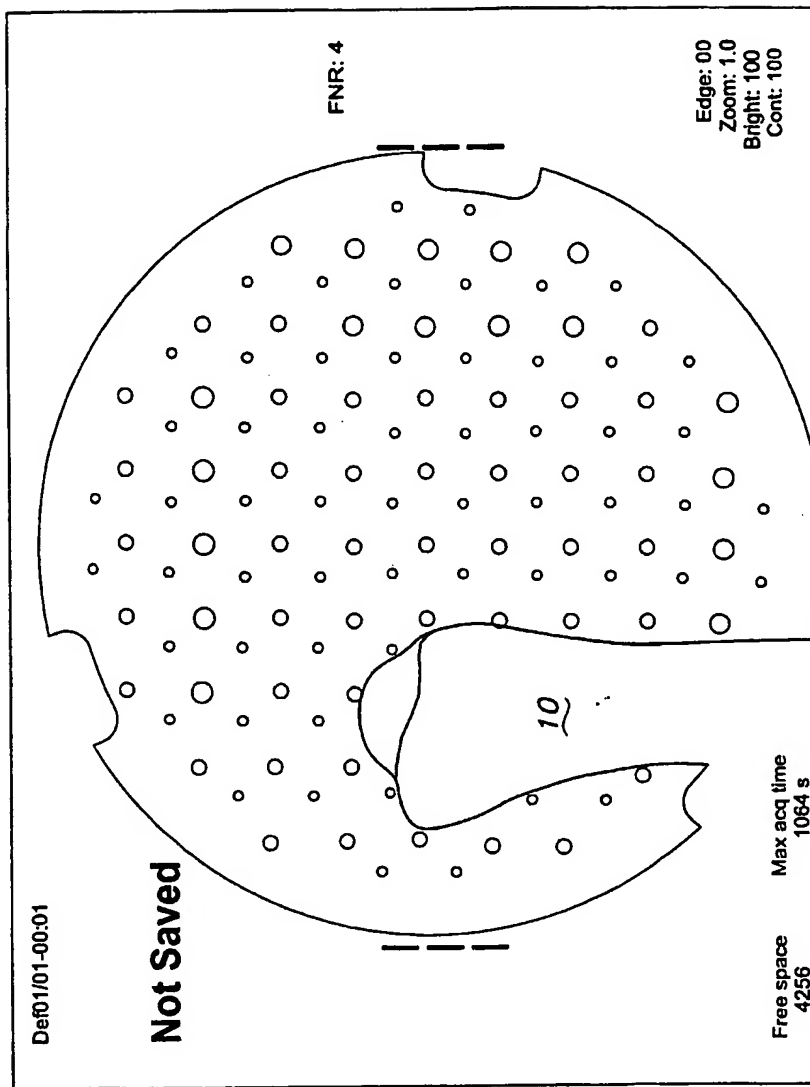
**FIG. 8**

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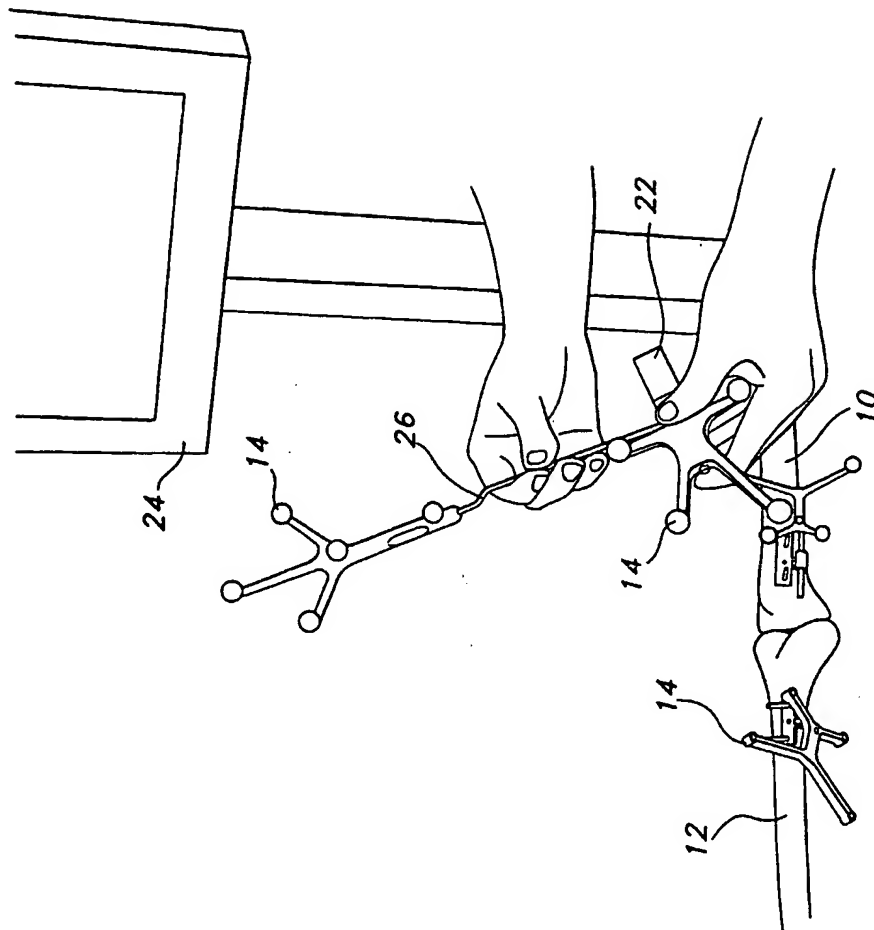
**FIG 9**

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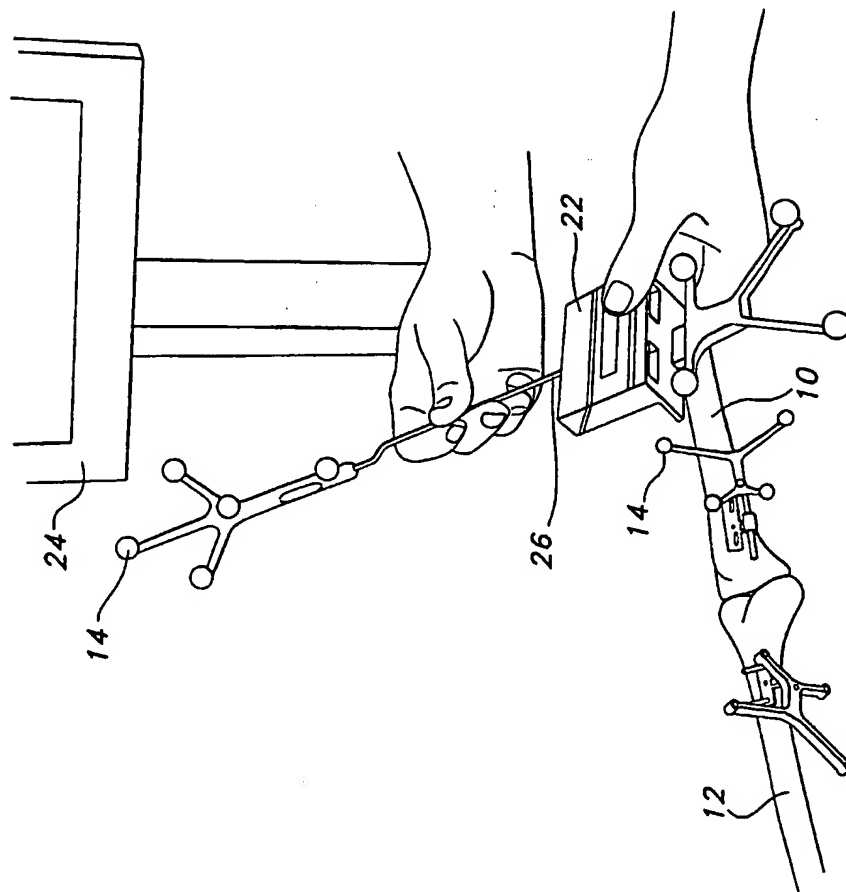
**FIG 10**

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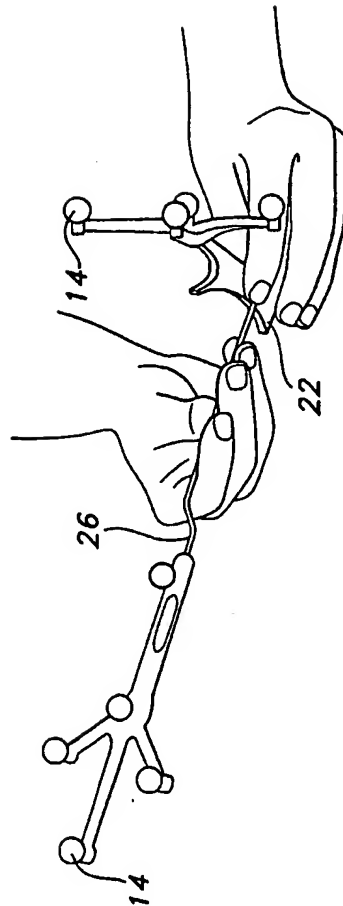
**FIG 11**

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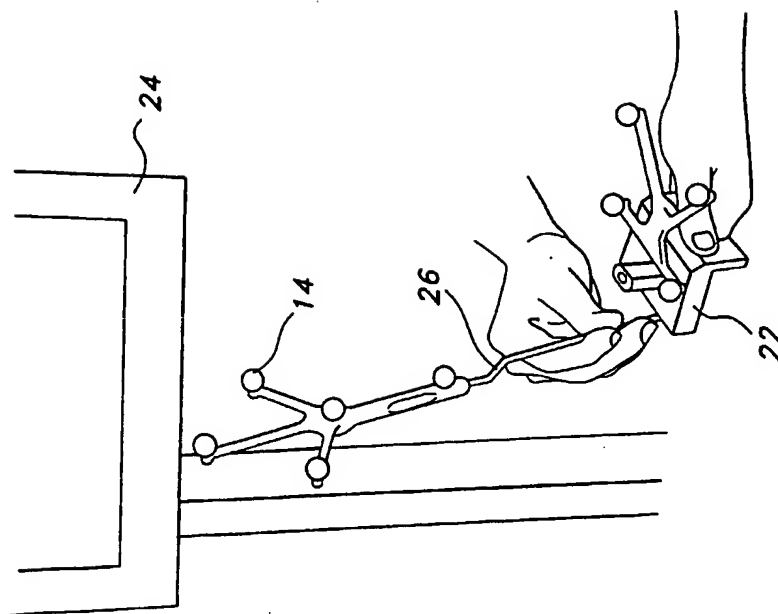
**FIG. 12**

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**FIG 13**

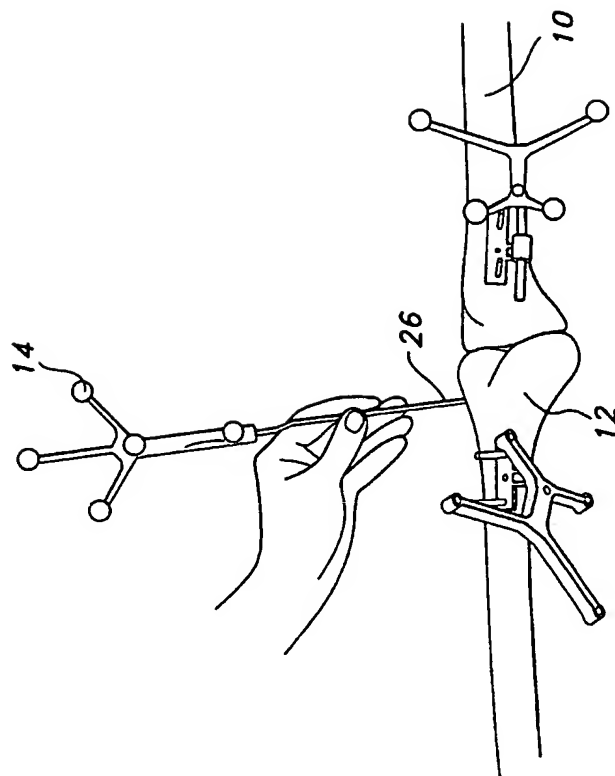
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**FIG 14**

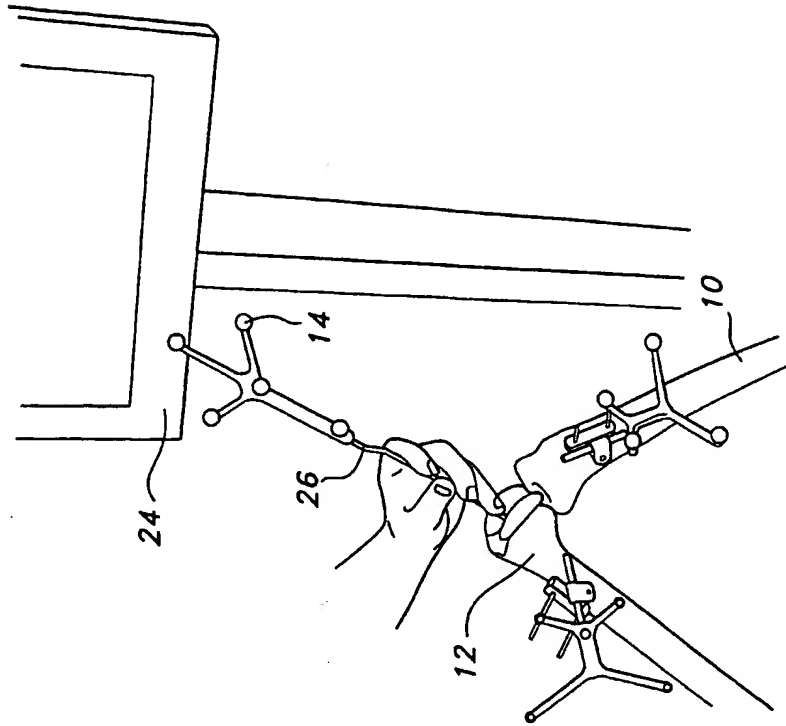


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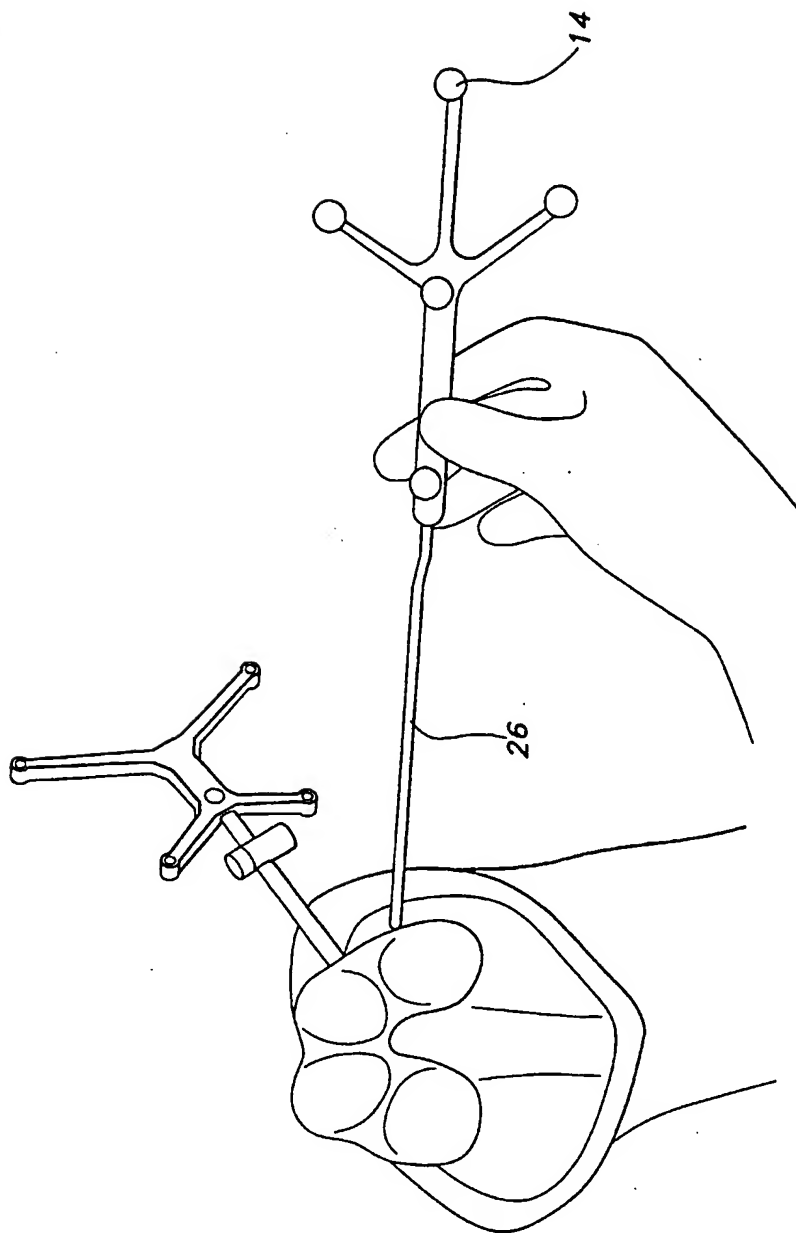
**FIG 15**

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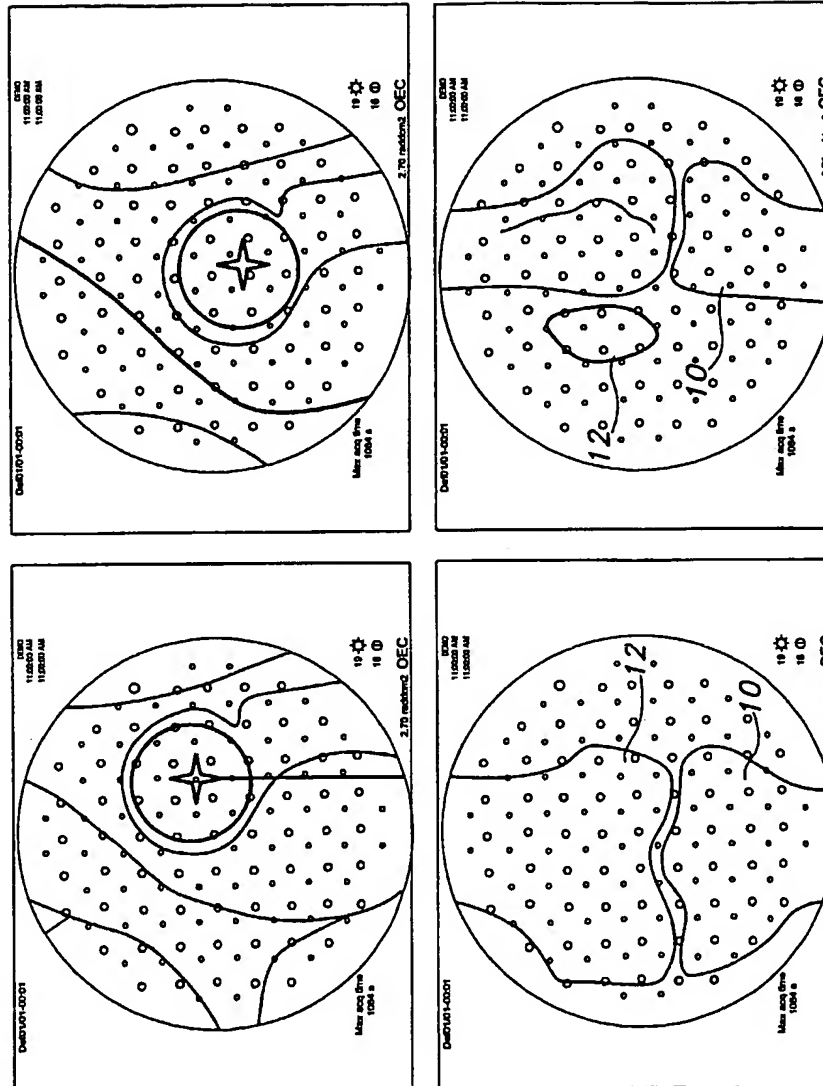
**FIG 16**

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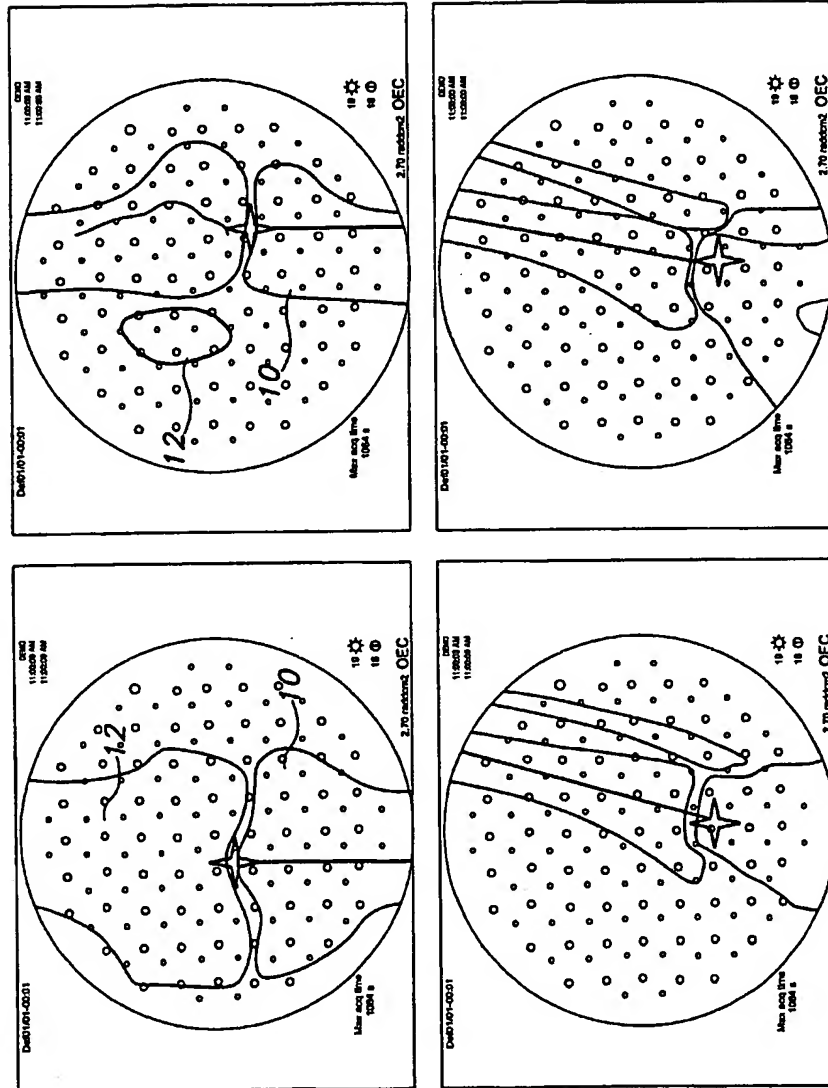
**FIG 17**

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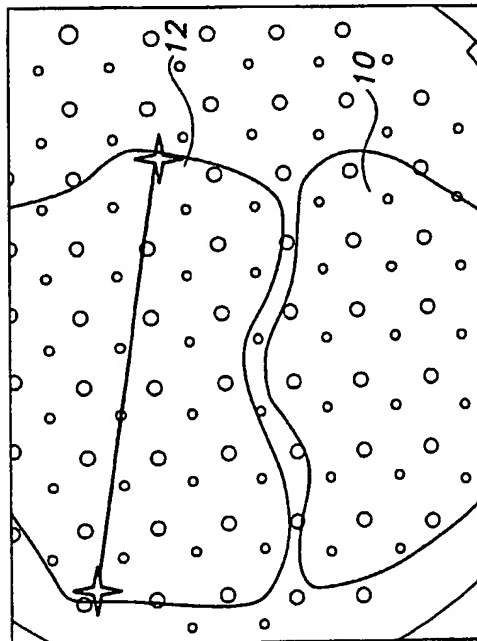
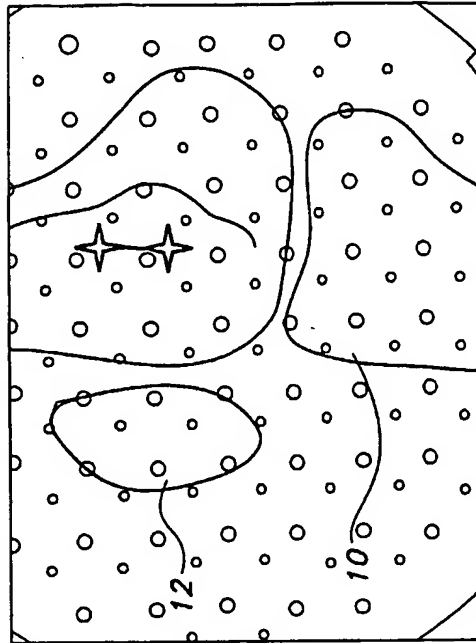
**FIG 18**

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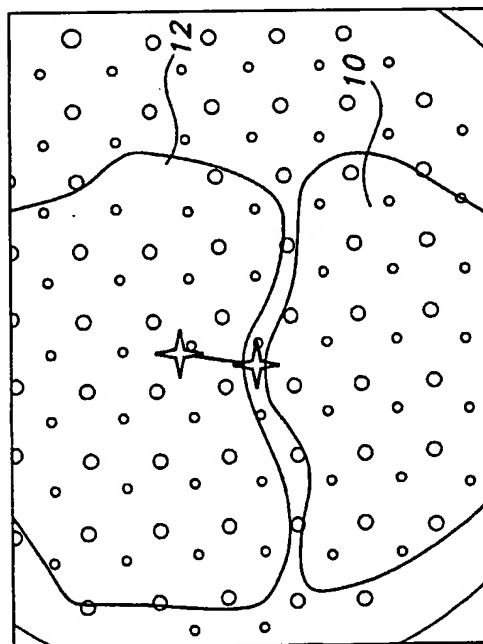
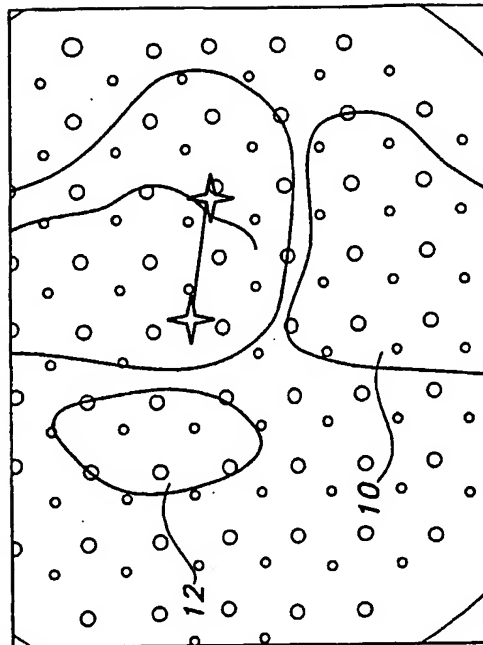
**FIG 19**

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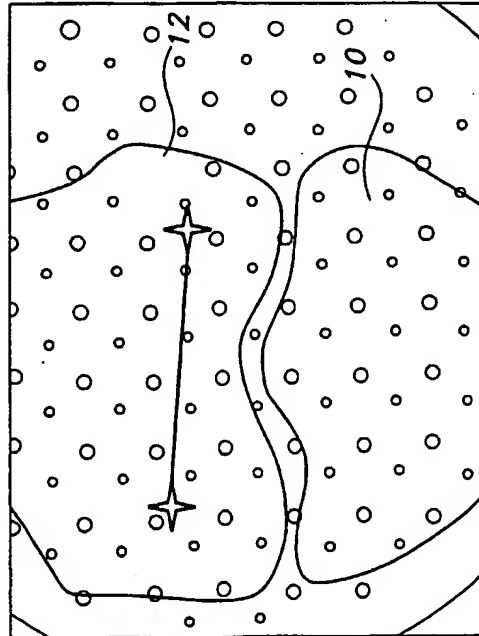
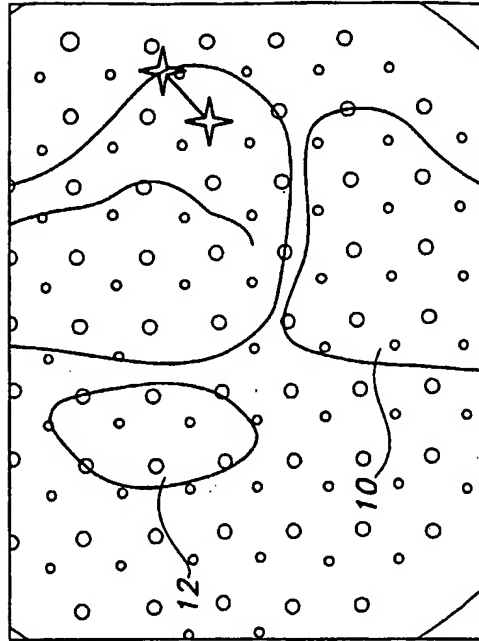
**FIG 20**

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**FIG 21**

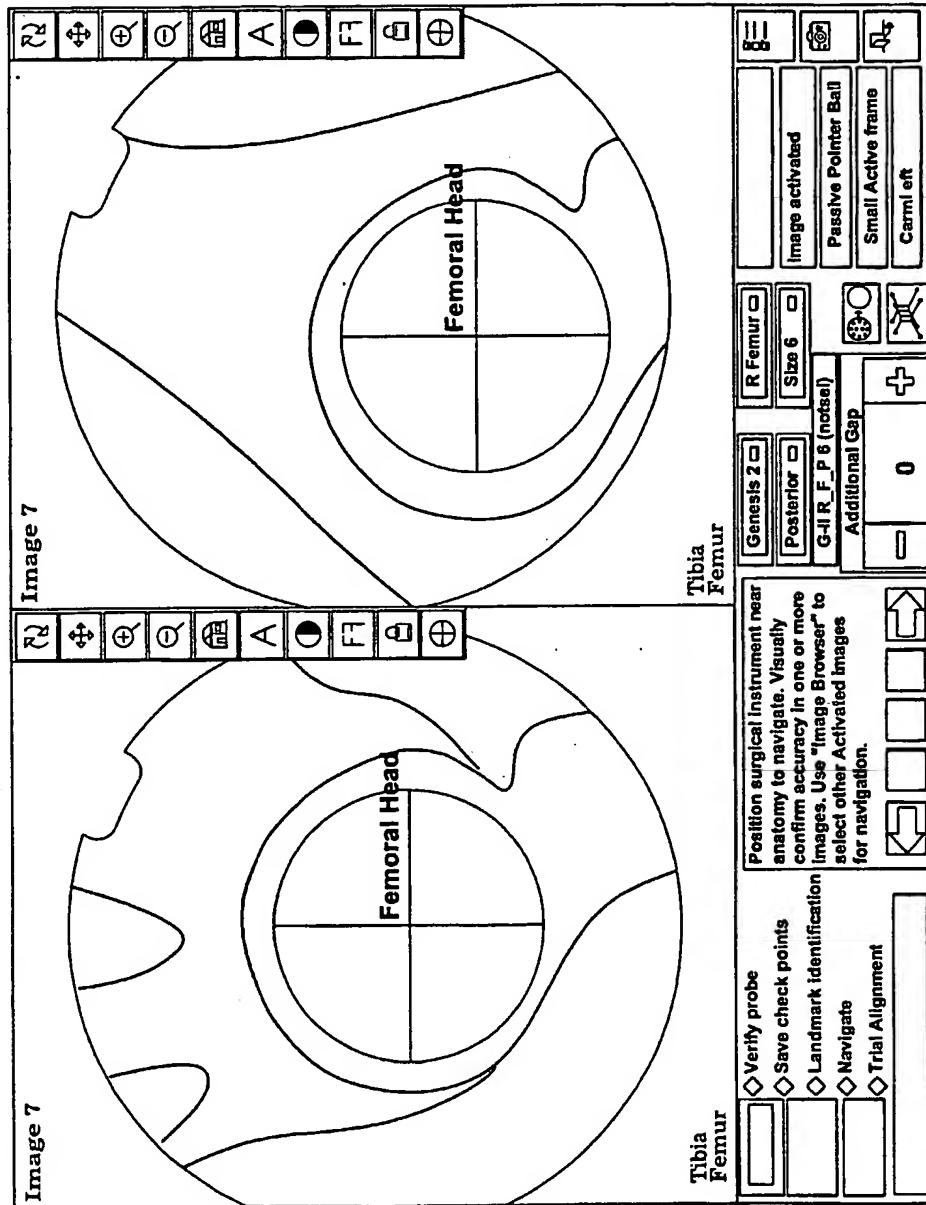
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**FIG 22**

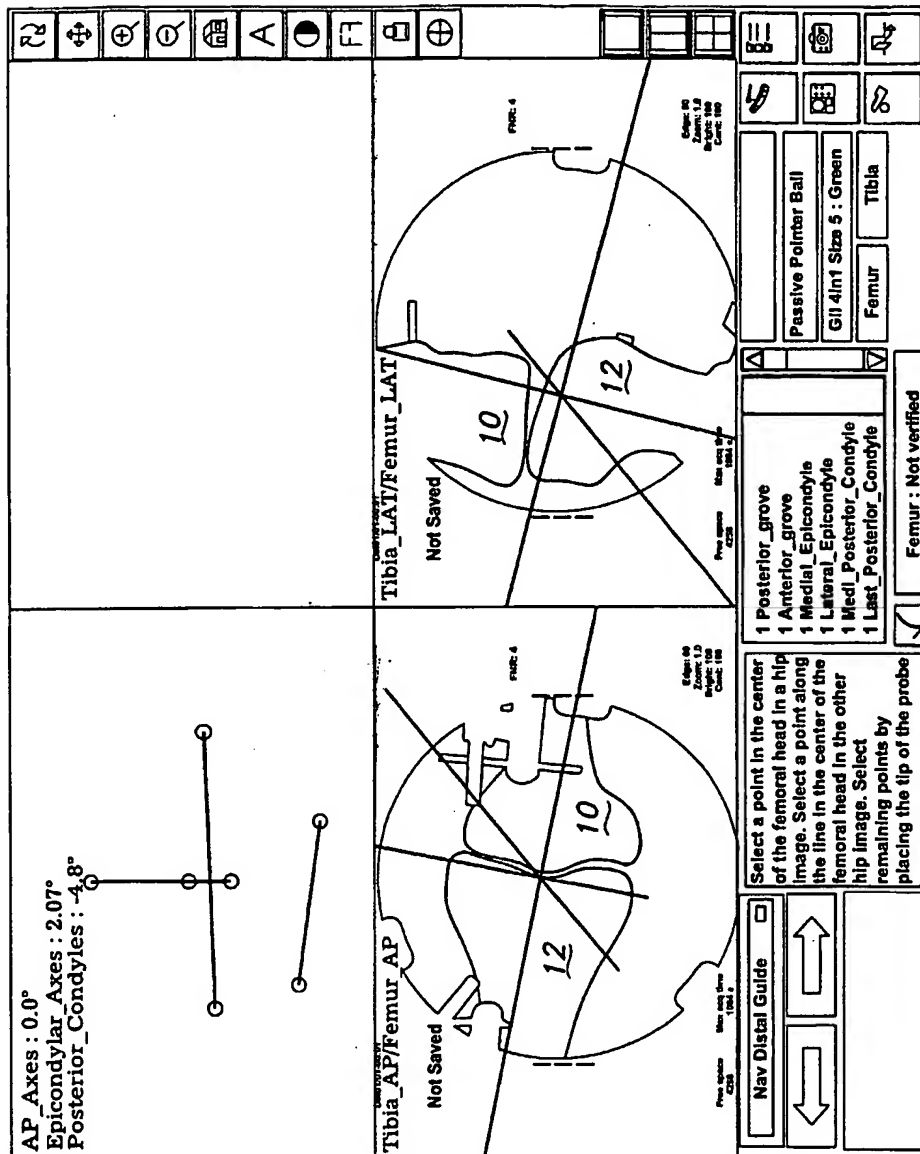


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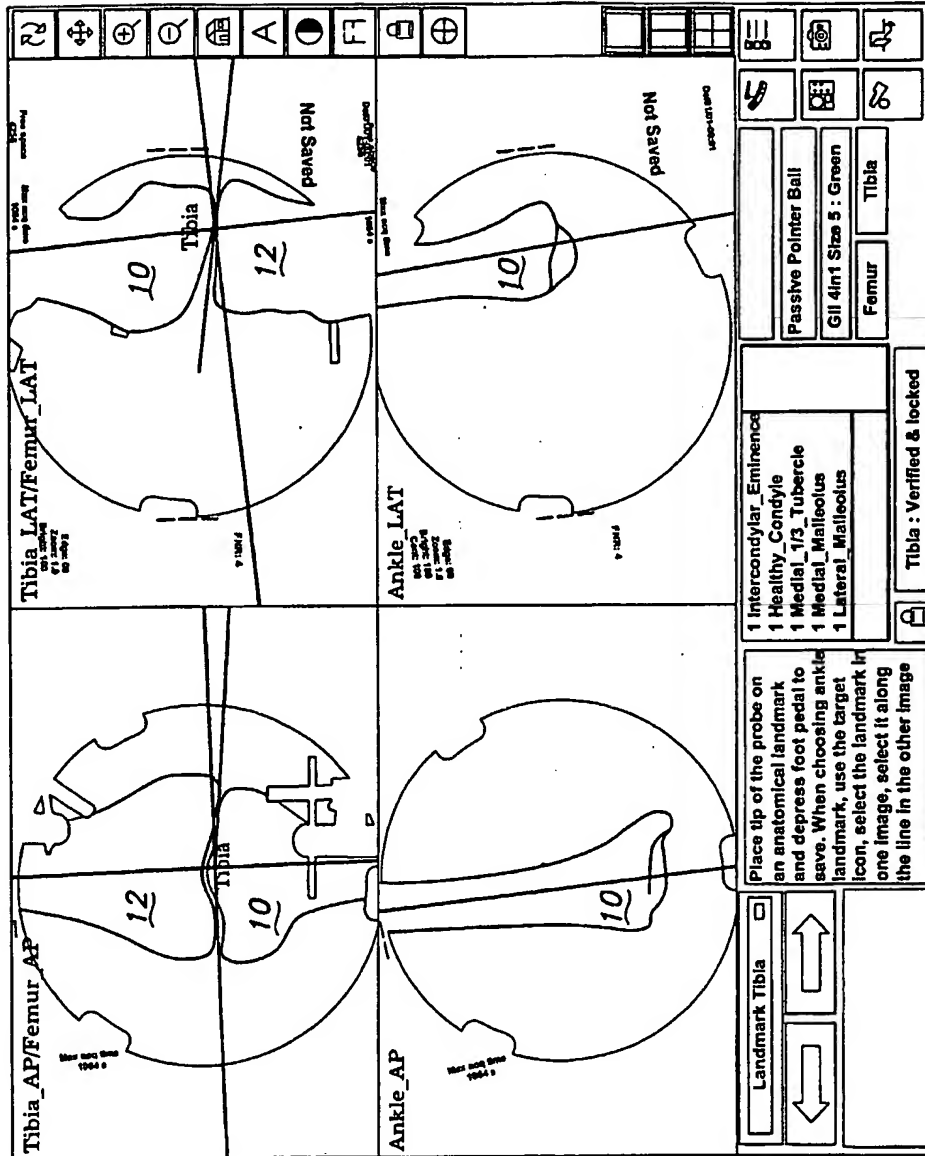
**FIG 23**

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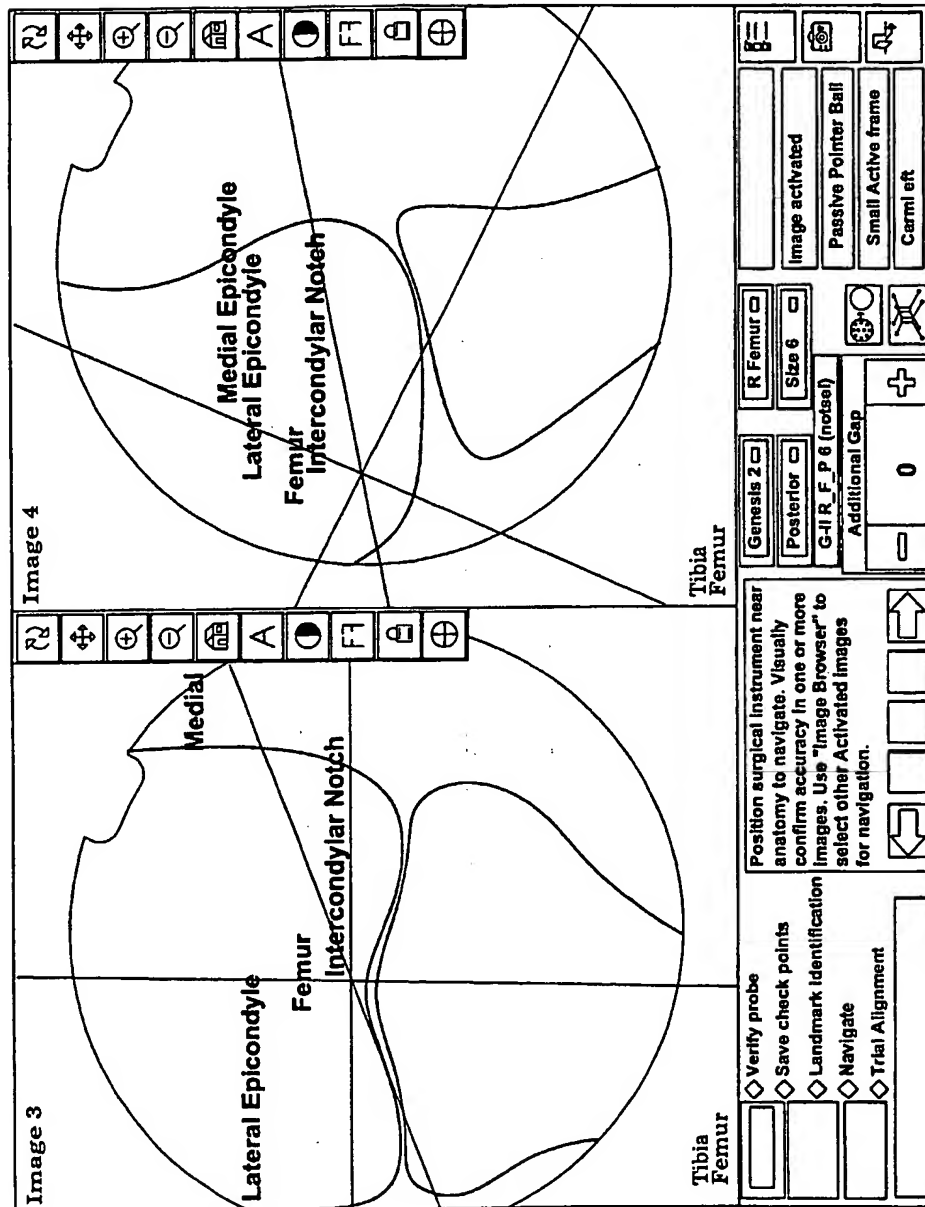


**FIG 24**

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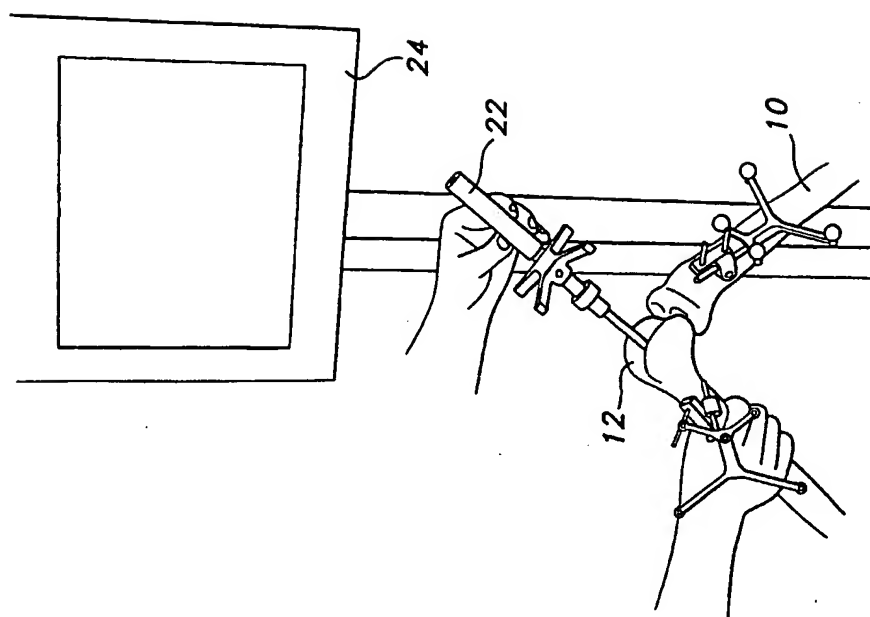


**FIG. 25**



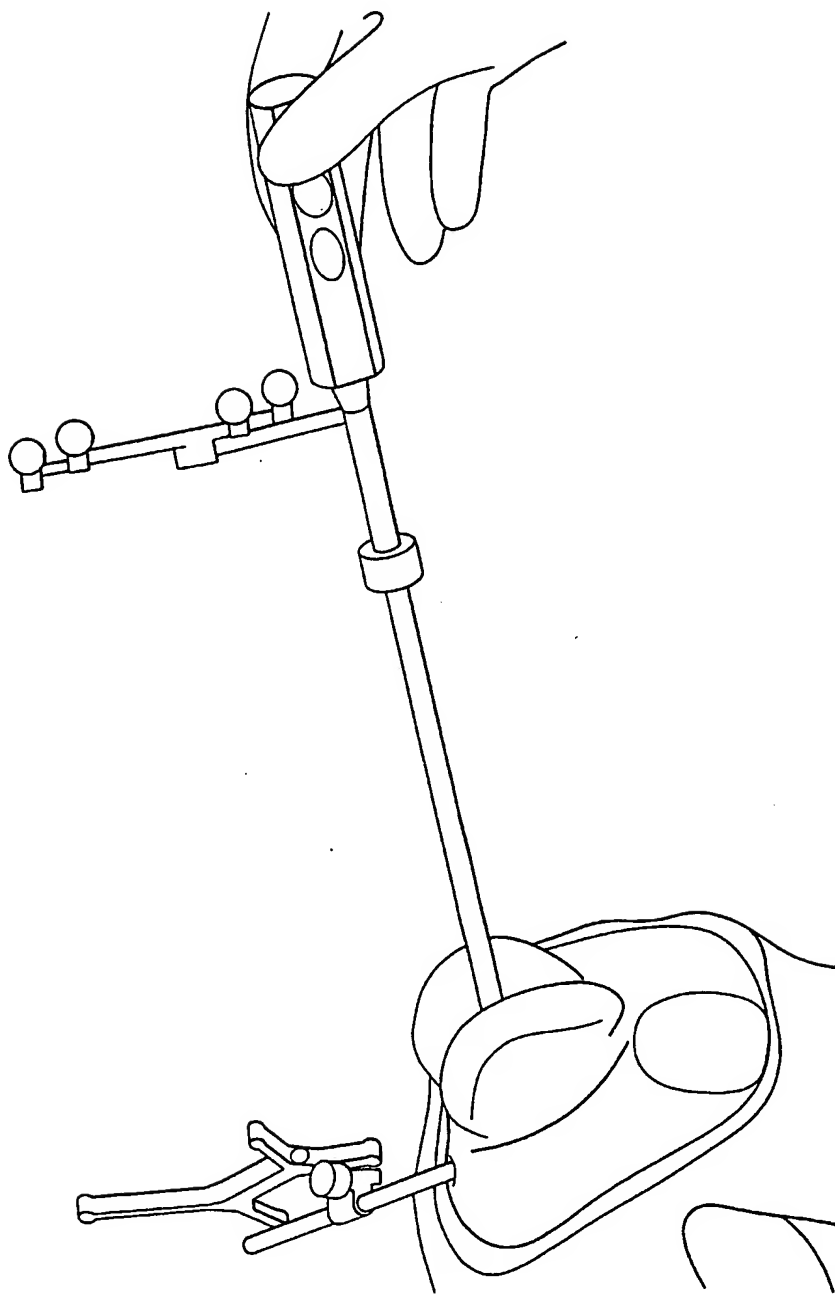
**FIG. 26**

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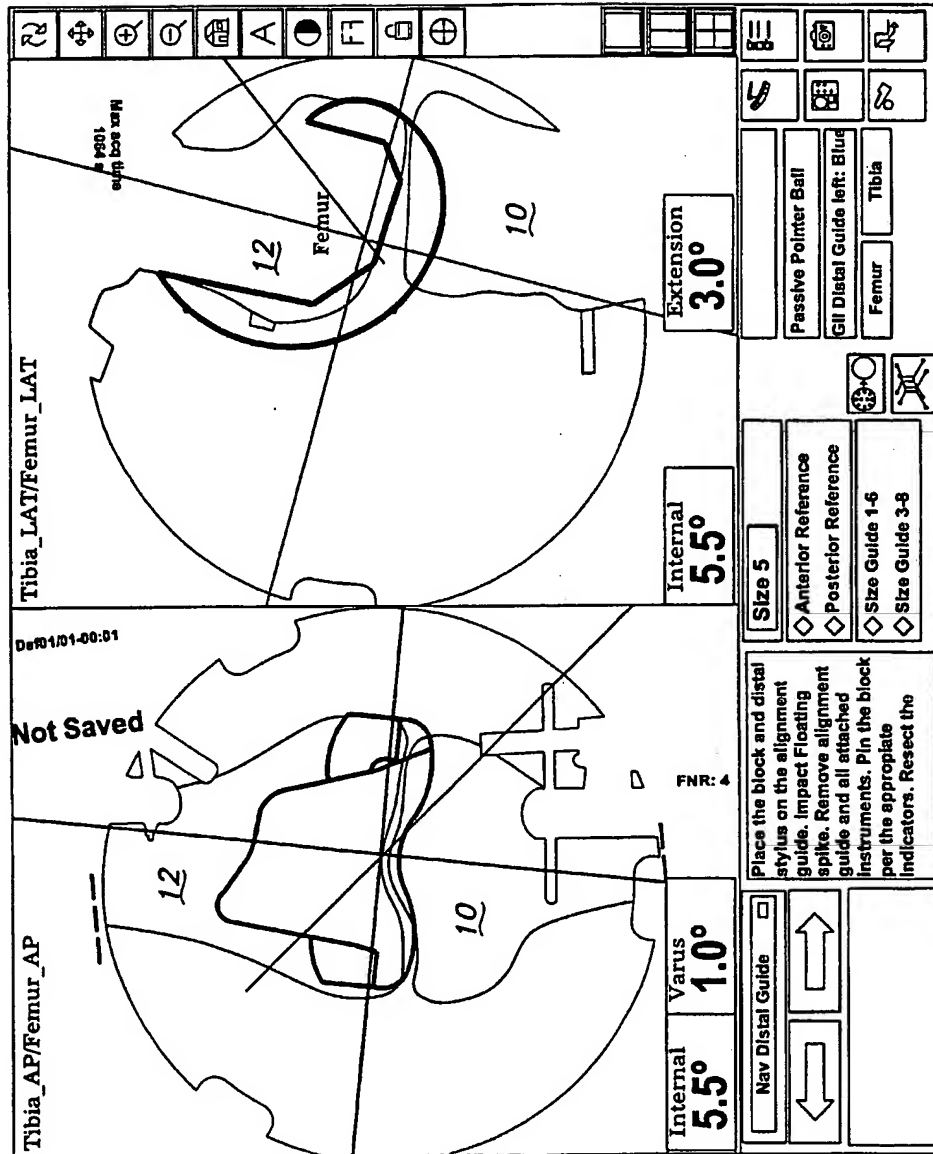
**FIG 27**

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**FIG 28**

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**FIG 29**

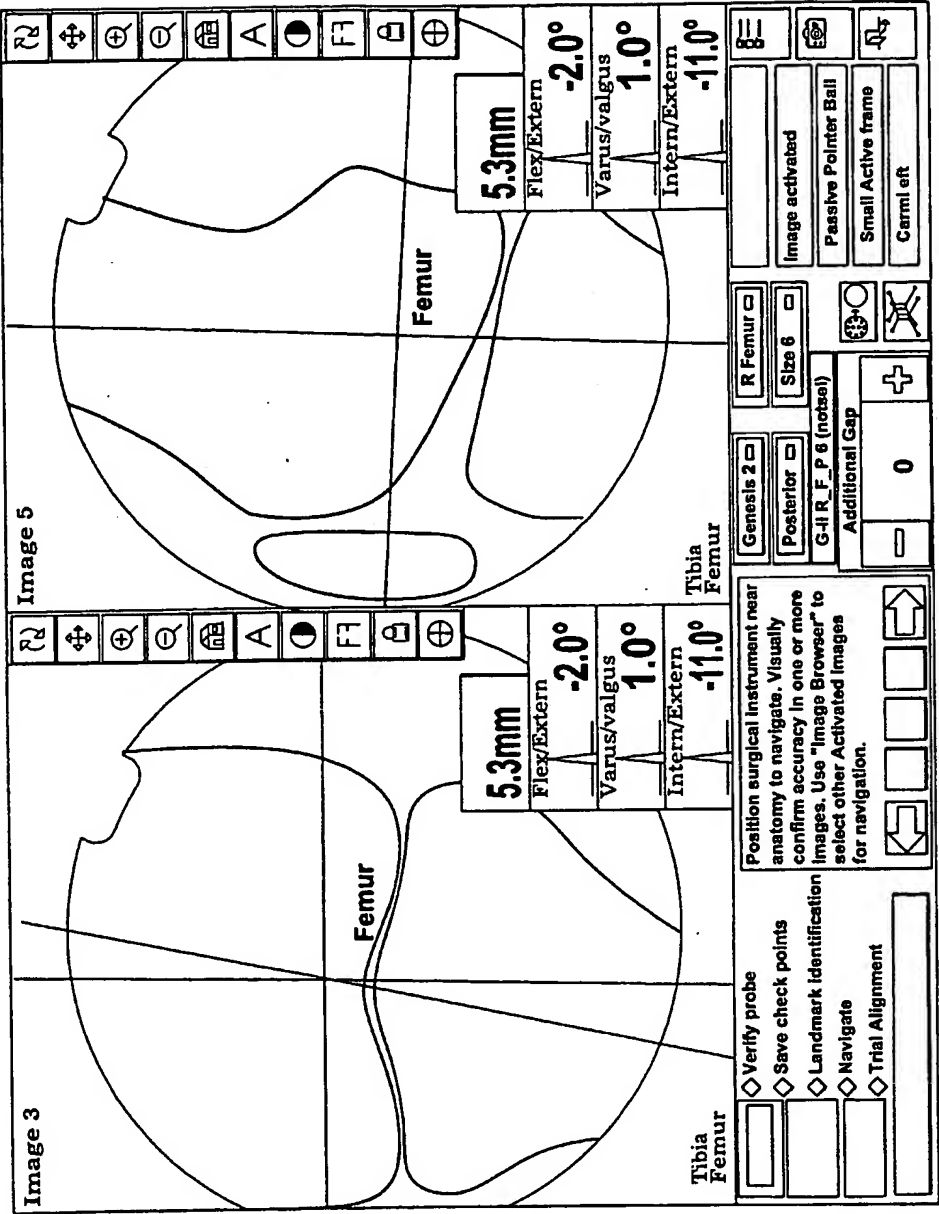
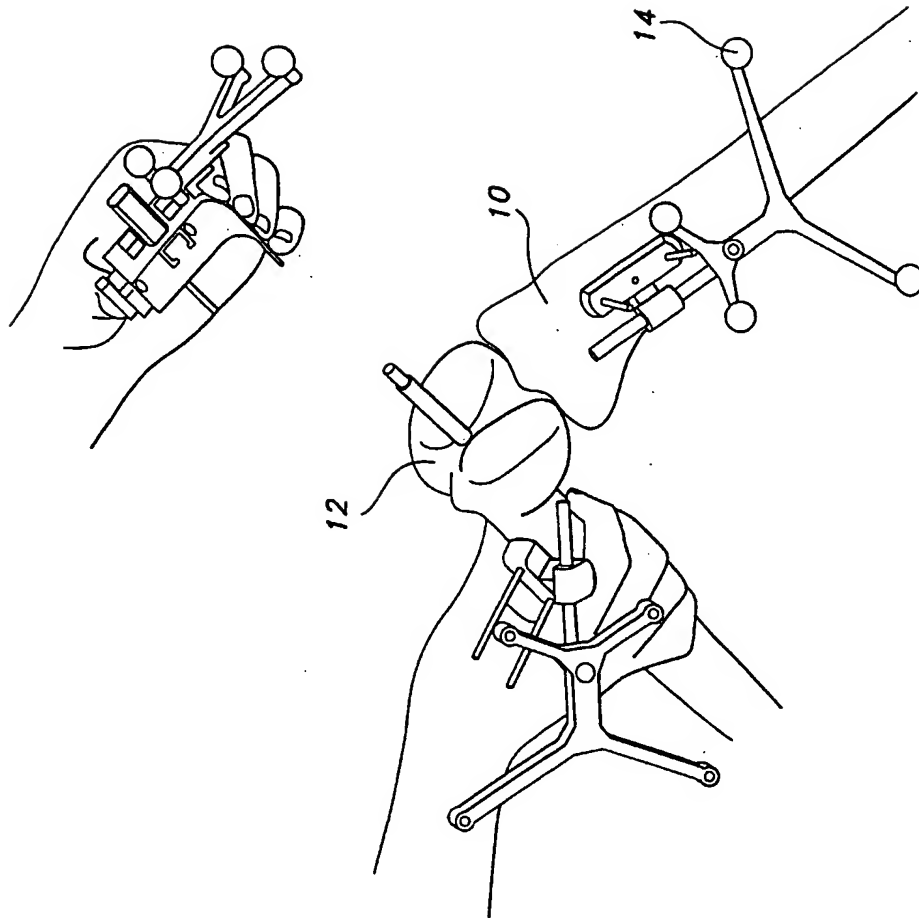


FIG 30

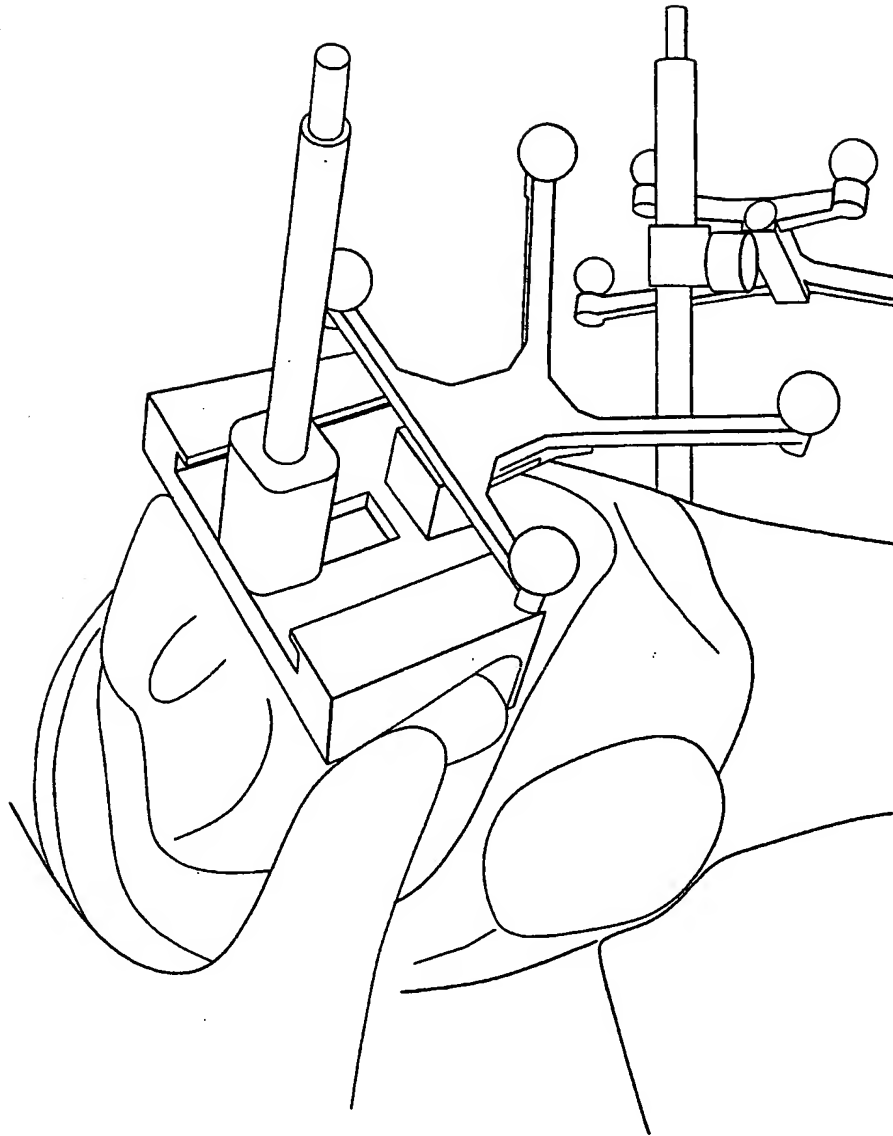


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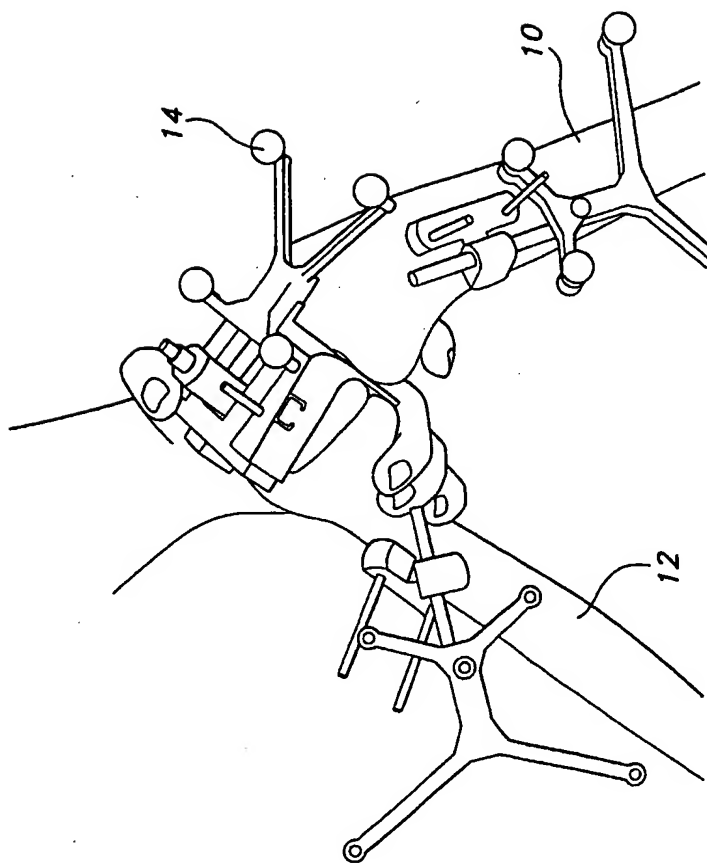
**FIG 31**

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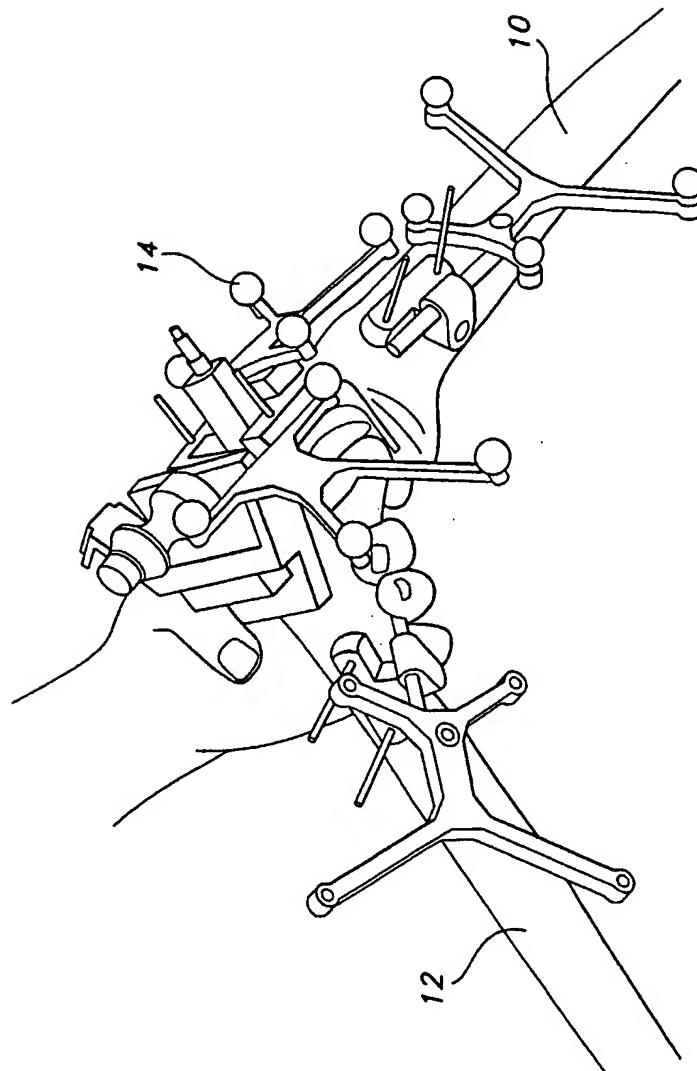
**FIG. 32**

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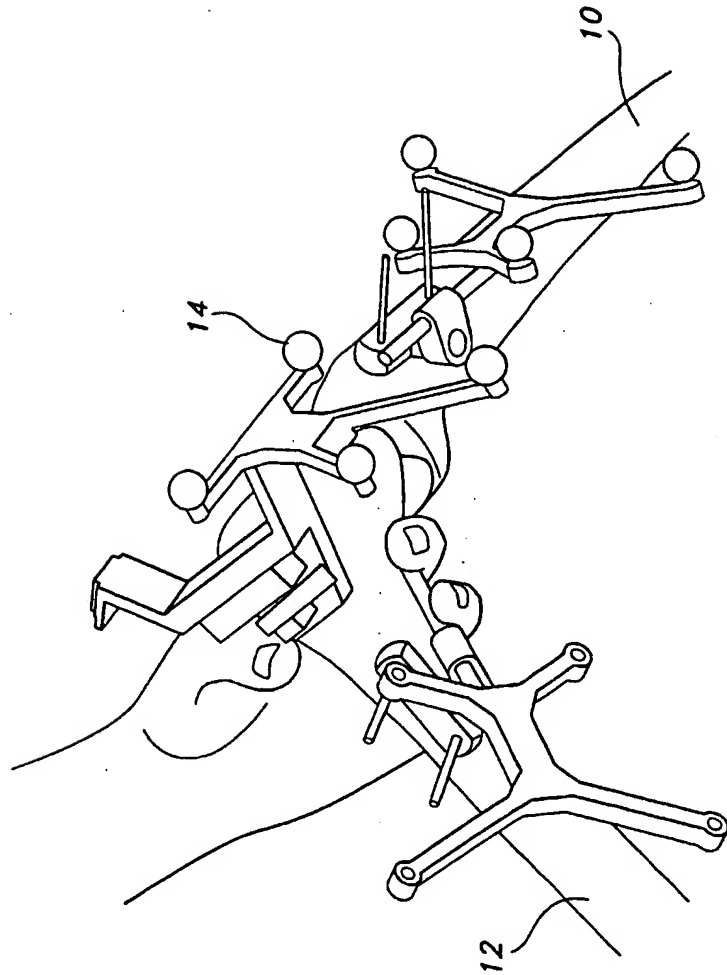
**FIG 33**

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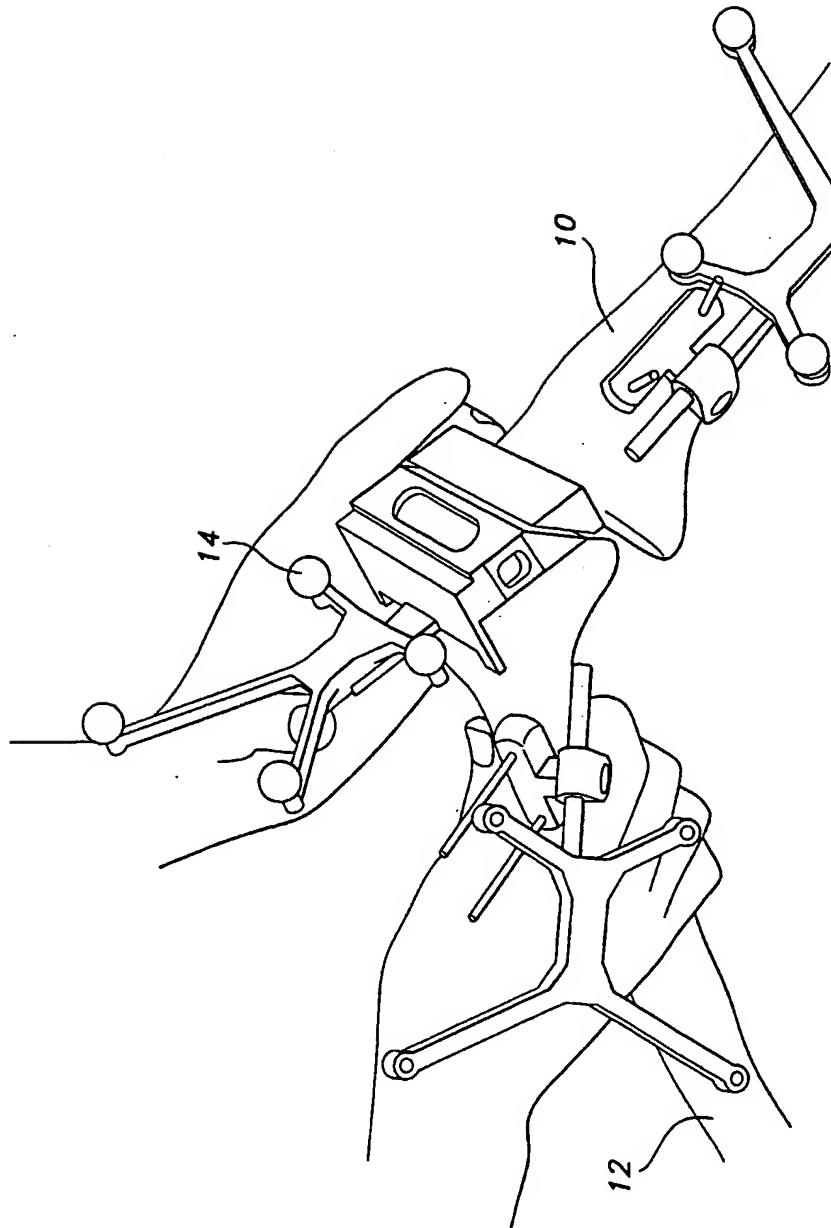
**FIG 34**

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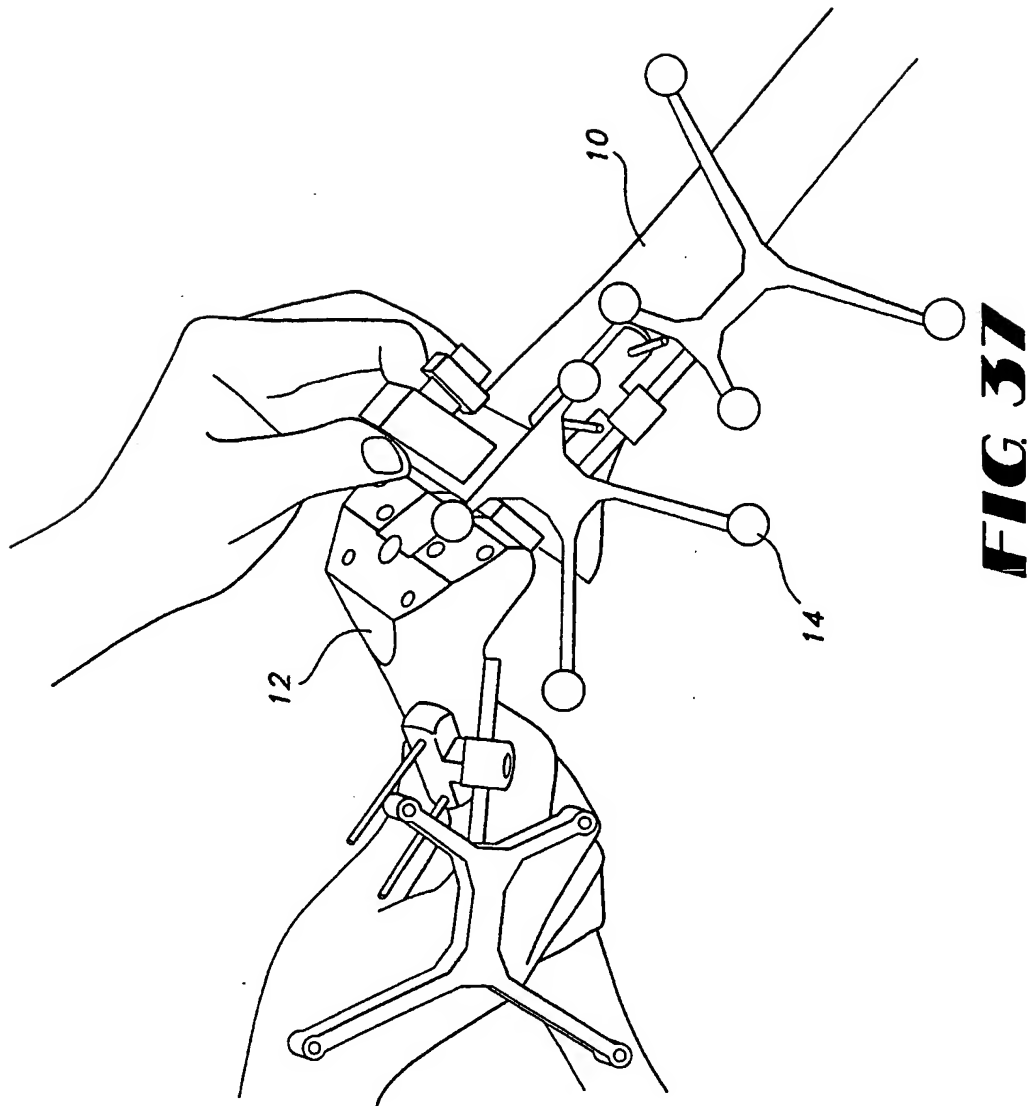
**FIG 35**

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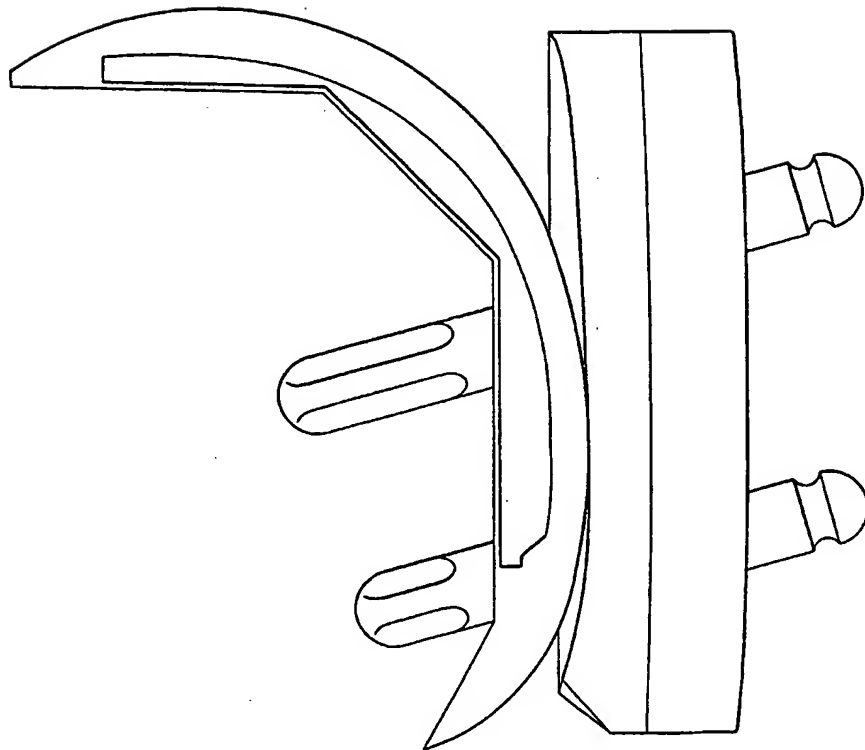
**FIG 36**

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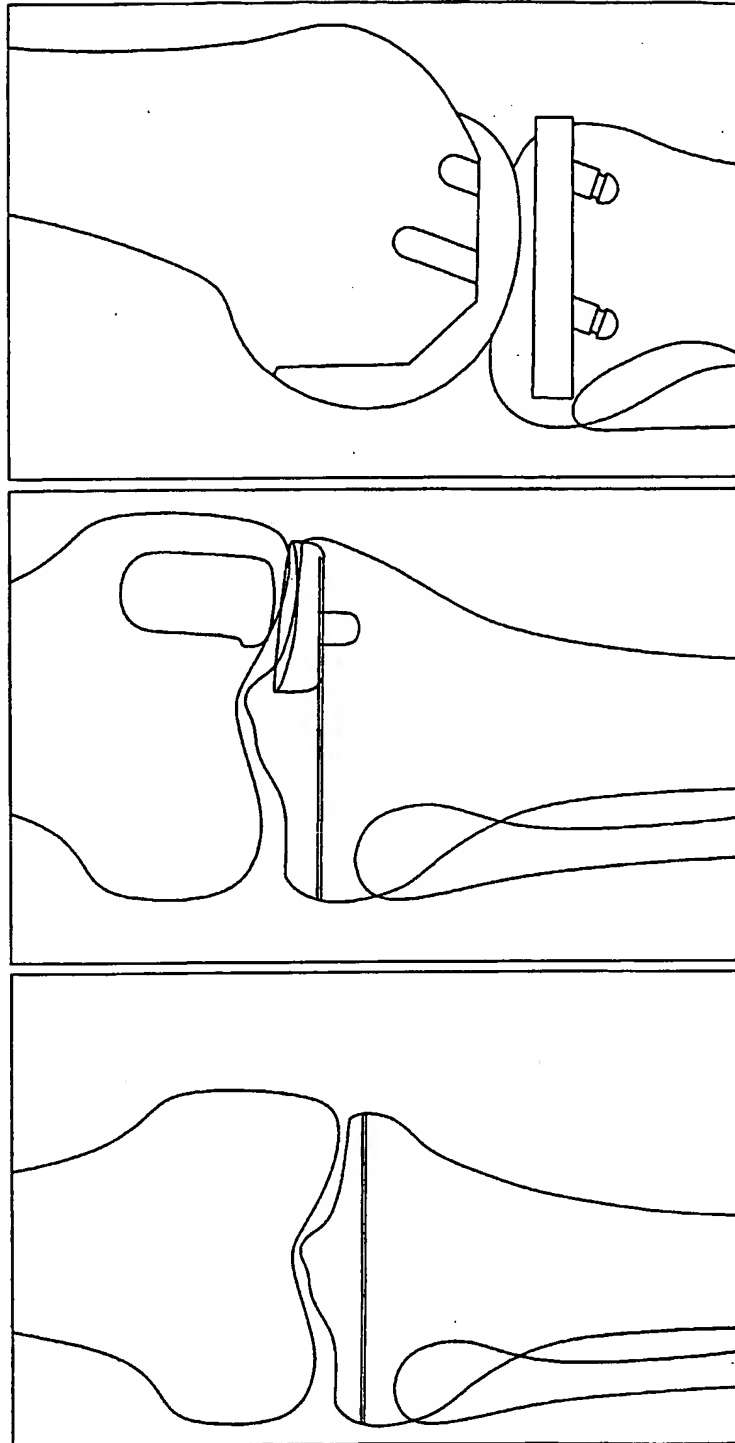
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**FIG 38**





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**FIG 39**

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